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Item 830-H-10

NAS 1.55:2137

DEC 2 4 1980

COMPLETED

NASA Conference Publication 2137

ORIGINAL

Propulsion Controls, 1979

Proceedings of a symposium held at Lewis Research Center
Cleveland, Ohio
May 17-19, 1979

NASA

153

NASA Conference Publication 2137

Propulsion Controls, 1979

Proceedings of a symposium
held at Lewis Research Center
Cleveland, Ohio
May 17-19, 1979

NASA
National Aeronautics
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**Scientific and Technical
Information Office**

1980

FOREWORD

In keeping with our mission of research on aeronautical propulsion systems, the Lewis Research Center has been engaged in studies of the control of high-performance airbreathing turbine engines by using advanced multivariable control theory. The 1979 Propulsion Controls Symposium brought together those interested in multivariable engine control to review the present state of the art, to determine future needs and problem areas, and to establish the appropriate roles of Government, industry, and universities in addressing these problems.

This symposium featured presentations on engine control design theory, applications, and related topics. In addition, a workshop session included in the symposium afforded each participant the opportunity to help resolve pertinent research questions and to direct future research efforts in multivariable engine control.

We hope this symposium proceedings will prove informative and useful to workers in the field.

Walter C. Merrill
Chairman

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ATEGG AND JTDE CONTROLS SUMMARY

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ABSTRACT

This presentation summarized Detroit Diesel Allison's control activities on the Advanced Turbine Engine Gas Generator (ATEGG) and Joint Technology Demonstrator Engine (JTDE) programs. A brief description of the ATEGG and JTDE control system hardware was followed by a discussion of the control logic. Engine self-trimming, sensor failure accommodation, engine diagnostics, staged combustion, and signal synthesis were addressed during this discussion, as well as automated control design techniques used to aid the control mode development. Control validation procedures were mentioned and led to presentation of results from recent ATEGG and JTDE tests.

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MULTIVARIABLE IDENTIFICATION USING CENTRALIZED FIXED MODES

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SUMMARY

A procedure to determine a state-space model of a multivariable system (ℓ inputs, m outputs) is presented. The model is suitable for control studies and uses single-input, single-output (SISO) system data in the identification procedure. The procedure can be defined in three distinct steps. First, the system's $\ell \times m$ SISO transfer functions are identified by using any standard or known identification technique for SISO systems. One objective of this step is to identify SISO transfer functions with as few distinct modes as possible between any two functions. Second, the time domain realization of each SISO transfer function is obtained in a straightforward manner and combined into a total multivariable realization. This total realization, in all probability, has more state variables than are required to define system response. In the third step, these excess or redundant states are removed by using minimal realization theory. The remaining states are related to system-centralized fixed modes. Eigenvalue-eigenvector techniques have recently been reported that yield a computationally feasible solution to the problem posed in step three. The procedure is applied to QCSEE data to demonstrate its feasibility.

INTRODUCTION

The application of modern control techniques to the design of turbine engine controls has established a need for state-space engine models. These models are required as input to the control design process. Previous work in this area has been accomplished by using (1) least-squares curve fitting combined with a dynamic nonlinear filter (ref. 1), (2) a perturbational method with an output error evaluation procedure (ref. 2), and (3) time-series analysis to find model-equivalent Kalman filters (ref. 3). These methods require special inputs or identification tests to generate data compatible with the identification process. Often it is not feasible or practical to perform special identification tests on turbine engines. Alternatively, engine test data may already be available but in a form incompatible with most identification techniques.

This paper presents a method that identifies state-space models without special restrictions on the test input or the engine test data. The method requires three steps. First, single-input, single-output (SISO) transfer functions for every input-output pair are identified from engine data. For a system with ℓ inputs and m outputs this results in $p = \ell \times m$ transfer functions. Second, a nonminimal state-space realization of these p transfer functions is

derived. Third, a minimal realization of the state-space model of step 2 is obtained by using the concept of centralized fixed modes (CFM) (ref. 4). The method is applied to a quiet, clean, short-haul experimental engine (QCSEE) to demonstrate its usefulness.

STEP 1

The use of transfer functions in this technique has several advantages over most conventional multivariable identification techniques. First, obtaining SISO transfer functions from real data is well understood. A large number of alternative techniques exist to identify transfer functions from virtually any type of data with predictable results (ref. 5). Second, use of transfer functions does not require simultaneous excitation of all inputs. Also, by determining transfer functions for each input-output pair considerable redundant information will be contained in these functions. This redundancy will reduce the noise and nonlinear effects inherent in the dynamic data.

STEP 2

Once the transfer functions are found, a state-space realization for each transfer function can be determined. These SISO state-space realizations can then be combined into a multivariable state-space realization. In general, this realization will be nonminimal. That is, more states are used than are actually required. These states are related to the redundant information inherent in the p SISO transfer functions. For example, consider a physical system modeled as third order. This system has two inputs and four outputs. Thus eight SISO transfer functions are of interest. Each transfer function can be first, second, or third order. If a state is assigned to each dynamic element of each transfer function, a realization of order 24 is obtained. This is clearly nonminimal since the system is assumed to be third order.

STEP 3

The third step finds the minimal realization of the state-space model by eliminating the redundant information inherent in the nonminimal realization of step 2. This is accomplished by using the concept of centralized fixed modes (CFM) (ref. 4). Minimal realization theory has its basis in filtering theory. Here the problem is to realize filter characteristics electrically by using the minimum number of inductors and capacitors. This theory has been generalized to multivariable systems (ref. 6). Additional information on minimal realizations can be found in reference 7. Although the theory of minimal realization for linear systems is well known, the actual determination of a minimal realization for high-order systems (order ≥ 10) is nontrivial. Computationally, the problem is one of finding k from

$$n = \text{Rank}\left\{B,\ AB,\ A^2B,\ \ldots,\ A^kB\right\} \tag{1}$$

when given n, A, and B. Practically, the problem becomes one of deciding when the differences of the large numbers of equation (1) become small enough to be considered zero. Different decisions imply different realizations. However, by applying the concept of CFM the practical minimal realization problem

implied in equation (1) can be solved by using eigenvector-eigenvalue techniques. These techniques are computationally quite robust and transfer the decision process from one of determining when the differences of large numbers are zero to the problem of deciding when two eigenvalues that are numerically close are for practical purposes the same eigenvalue. By relating eigenvalues to physically observable system dynamic modes, physical insight can be easily incorporated in the decision process, whereas this is not the case in equation (1).

Consider the nonminimal system of figure 1. As the output feedback gain matrix K is allowed to vary, some modes of this closed-loop system will remain constant. These modes are the CFM's. They correspond to those modes that are unobservable or uncontrollable and that represent redundant (or useless from a controls point of view) information. An algorithm to find these modes then will be to find the eigenvalues of the closed-loop system at two randomly chosen values of K. The CFM's are simply those modes in the intersection of these two sets of eigenvalues. Once the CFM's are known, the eigenvectors corresponding to the remaining modes can be used to construct a minimal realization (ref. 4).

QCSEE EXAMPLES

This technique was applied to the QCSEE under-the-wing (UTW) turbofan engine (ref. 8). This engine has three inputs

XMV	fuel-metering-valve position
X18	fan-nozzle-area actuator position
θ_I	fan-pitch-mechanism drive motor position

and five outputs

NL	fan rotor speed
NH	compressor rotor speed
PS11	engine-inlet static pressure
PS3C	compressor discharge pressure
P4GS	combustor discharge pressure

Step 1

Transfer functions were determined from normalized dynamic simulation data by the extended, adjustable-parameter-vector recursive identification technique (ref. 9). The functions were obtained at an intermediate (80 percent of maximum) power condition. A pseudorandom binary sequence was used as input to the simulation. The sequence amplitude was selected to achieve 5 percent of nominal perturbations in the control variable in order to maintain linearity. Steady-state accuracy was improved by incorporating step-response information. Three of the 15 functions were found to be zero, and the 12 remaining functions were all first order. Actual identified results determined 12 distinct eigenvalues or poles of the system. However, it was observed that the eigenvalues were contained in four distinct groups. Further, by changing the values of the eigenvalues by no more than ± 10 percent of their identified value, four distinct eigenvalues result. A change of 10 percent in a system eigenvalue has no significant dynamic effect. This consolidation of eigenvalues allows the possi-

bility of a fourth-order realization, whereas no reduction would be possible if all 12 eigenvalues were distinct. The transfer functions are given in figure 2.

Step 2

Twelve first-order differential equations were found which realize the 12 transfer functions by assigning one state to each transfer function. The 12 first-order equations were then combined into the state-space matrix equation of order 12 given in figure 3.

Step 3

The state-space realization of step 2 was reduced by using the CFM concept. Thw two feedback matrices were selected as $K = 0$ and

$$K = \begin{bmatrix} 10 & 2 & 11 & -8 & -12 \\ 13 & 7 & 13 & 14 & 9 \\ -25 & -8 & 18 & 22 & 17 \end{bmatrix} \qquad (2)$$

The eigenvalues are known in the open-loop case ($K = 0$), and they were calculated for the randomly selected K matrix of equation (2). The modes are given in table I. Six exact CFM's were found. When these modes are eliminated, a sixth-order exact realization of the 12 transfer functions results.

Note that the closed-loop modes 6 and 7 closely approximate their open-loop counterpart. The difference is less than 5 percent. If these modes of $A + BKC$ always remain close to the modes of A for different K, they are called approximate CFM's. When these approximate CFM's are eliminated, the approximate minimal realization that results will be a good approximation to the given transfer functions (ref. 4). The eight CFM's were removed, leaving the fourth-order realization of figure 4.

Comparison of the given transfer functions of step 1 with those of the fourth-order realization shows good agreement (fig. 5). When poles and zeros of approximately the same magnitude are cancelled (within $\pm$10 percent), the transfer functions of figures 2 and 5 compare one to one in structure with good magnitude agreement in all cases except for NH/XMV, NH/X18, and P4GS/X18. A comparison of Bode magnitude and phase plots for these three cases shows, however, that the dynamic content of the original transfer functions is accurately reproduced. Since the NH/XMV characteristic is the least accurately reproduced of the three, this Bode response is shown in figure 6. The dynamics are closely modeled, with only a dc offset error.

SUMMARY OF RESULTS

A three-step process was developed for the identification of state-space models of multivariable turbine engines. The three steps are (1) identification of SISO transfer functions, (2) nonminimal realization of the SISO transfer functions in state-space form, and (3) construction of a minimal realization from the results of step 2 by using the concept of CFM's. This three-step process was applied to the QCSEE example - a three-input, five-output turbofan

engine. The SISO transfer functions were found for an intermediate operating point by using the extended, adjustable-parameter-vector recursive identification technique. A fourth-order, approximate, minimal, state-space realization was then obtained which accurately models the SISO transfer functions of the engine. Thus a multivariable state-space model of QCSEE was obtained.

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TABLE I. - DYNAMIC MODES OF QCSEE EXAMPLE

Mode	Modes (negative)			
	Open loop (K = 0)	Closed loop (K of eq. (2))	Centralized fixed	Approximate centralized fixed
1	3	3	×	
2	3	102		
3	4	4	×	
4	↓	4	×	
5		4	×	
6		4.0004		×
7		3.84		×
8		6.5 + 1.2j		
9	6	6.5 - 1.2j		
10	6	6	×	
11	7.4	7.4	×	
12	7.4	-203		

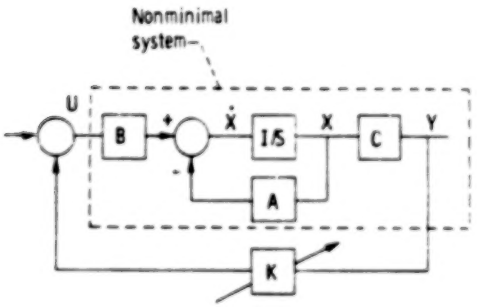


Figure. 1 - Nonminimal state-space system with output feedback.

Output: \ Input:	XMV	X1B	θ_1
NL	$\frac{1.974}{s+3}$	$-0.029503 + \frac{0.498}{s+4}$	$\frac{2.48}{s+4}$
NH	$\frac{1.0824}{s+4}$	$0.009111 + \frac{0.0128}{s+4}$	$\frac{-0.046}{s+4}$
PS1I	$-7.15882 + \frac{18.55561}{s+3}$	$-0.194411 + \frac{(-0.0719)}{s+6}$	0
PS3C	$0.701750 + \frac{2.4912}{s+7.4}$	$0.0048148 + \frac{(-0.00549)}{s+6}$	0
P4GS	$0.582174 + \frac{3.4523}{s+7.4}$	$0.0031907 + \frac{0.003637}{s+4}$	0

Figure 2. - Identified transfer functions for QCSEE example (step 1).

$$A = \mathrm{Diag}\{-3, -4, -4, -4, -4, -4, -3, -6, -7.4, -6, -7.4, -4\}$$

$$B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -16.88 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 1.4 & 0 \\ 0 & 0 & 1 \\ -2.592 & 0 & 0 \\ 0 & .37 & 0 \\ 3.55 & 0 & 0 \\ 0 & -1.14 & 0 \\ 5.93 & 0 & 0 \\ 0 & 1.14 & 0 \end{bmatrix} \qquad C^T = \begin{bmatrix} 1.974 & 0 & 0 & 0 & 0 \\ -.029503 & 0 & 0 & 0 & 0 \\ 2.48 & 0 & 0 & 0 & 0 \\ 0 & 1.0824 & 0 & 0 & 0 \\ 0 & .009111 & 0 & 0 & 0 \\ 0 & -.046 & 0 & 0 & 0 \\ 0 & 0 & -7.1588 & 0 & 0 \\ 0 & 0 & -.194411 & 0 & 0 \\ 0 & 0 & 0 & .70175 & 0 \\ 0 & 0 & 0 & .0048148 & 0 \\ 0 & 0 & 0 & 0 & .582174 \\ 0 & 0 & 0 & 0 & .0031907 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & -0.209503 & 0 \\ 0 & .009111 & 0 \\ -7.15882 & -.19411 & 0 \\ .70175 & .0048148 & 0 \\ .582174 & .0031907 & 0 \end{bmatrix}$$

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

Figure 3. - Step 2 nonminimal state-space realization.

$$A = \begin{bmatrix} -2.24662 & -1.16546 & -0.418183 & -0.272656 \\ 1.07843 & -4.74978 & .150263 & -.399761 \\ -.222253 & .213179 & -6.04245 & .777190\text{-}01 \\ 11.0705 & -7.55947 & -.874397 & -7.37052 \end{bmatrix}$$

$$B = \begin{bmatrix} 6.73867 & 0.973885\text{-}01 & 0.629103 \\ -1.69887 & .195782 & .956754 \\ .272735 & -.160244 & .292572\text{-}01 \\ -.120195\text{-}01 & -.152280 & -.865623\text{-}01 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.799406 & 2.03487 & 0.141594 & -0.307101 \\ .133325 & -.132226 & -.787788\text{-}01 & .414125\text{-}01 \\ 2.36230 & -1.55349 & -.280536\text{-}02 & -.115033\text{-}02 \\ .311503 & -.218147 & .711449\text{-}01 & -.123842 \\ .434379 & -.302254 & .484864\text{-}01 & -.165305 \end{bmatrix}$$

$$D = \begin{bmatrix} 0.000000 & -0.029503 & .000000 \\ .000000 & .009111 & .000000 \\ -7.15882 & -.194411 & .000000 \\ .701750 & .481148\text{-}02 & .000000 \\ .582174 & .319070\text{-}02 & .000000 \end{bmatrix}$$

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

Figure 4. - Fourth-order approximate minimal realization of QCSEE example.

Output:	Input: XMV	X18	I_θ
NL	$\frac{1.97(s + 3.82)(s + 6.03)(s + 7.2)}{\text{DENOM}^a}$	$-0.029503 + \frac{0.5(s + 2.97)(s + 6.02)(s + 7.4)}{\text{DENOM}}$	$\frac{2.48(s + 2.98)(s + 6.02)(s + 7.4)}{\text{DENOM}}$
NH	$\frac{1.1(s + 4)(s + 6.0)(s + 10.0)}{\text{DENOM}}$	$0.00911 + \frac{-0.0066(s + 3.05)(s + 7.33 + 0.168_j)}{\text{DENOM}}$	$\frac{-0.0485(s + 2.98)(s + 6.02)(s + 7.4)}{\text{DENOM}}$
PS11	$-7.15882 + \frac{18.6(s + 4)(s + 6.08)(s + 7.34)}{\text{DENOM}}$	$-0.194411 + \frac{-0.0735(s + 3.27)(s + 4)(s + 7.4)}{\text{DENOM}}$	$\frac{-0.00016(s + 4.07)(s + 7.4)(s + 15)}{\text{DENOM}}$
PS3C	$0.701750 + \frac{2.49(s + 2.95)(s + 4)(s + 6)}{\text{DENOM}}$	$0.0048148 + \frac{-0.0049(s + 2.97)(s + 4)(s + 7.46)}{\text{DENOM}}$	$\frac{0.000056(s + 3)(s + 3.9)(s + 6.8)}{\text{DENOM}}$
P4GS	$0.582174 + \frac{3.46(s + 3.15)(s + 4)(s + 6.02)}{\text{DENOM}}$	$0.0031907 + \frac{0.00053(s + 2.6)(s + 3.86)(s + 6.93)}{\text{DENOM}}$	$\frac{-0.000186(s + 3)(s + 7.95)(s + 6.0)}{\text{DENOM}}$

[a]DENOM = (s + 2.98)(s + 4)(s + 6.02)(s + 7.4)

Figure 5. - Fourth-order approximate realization of QCSEE example transfer function.

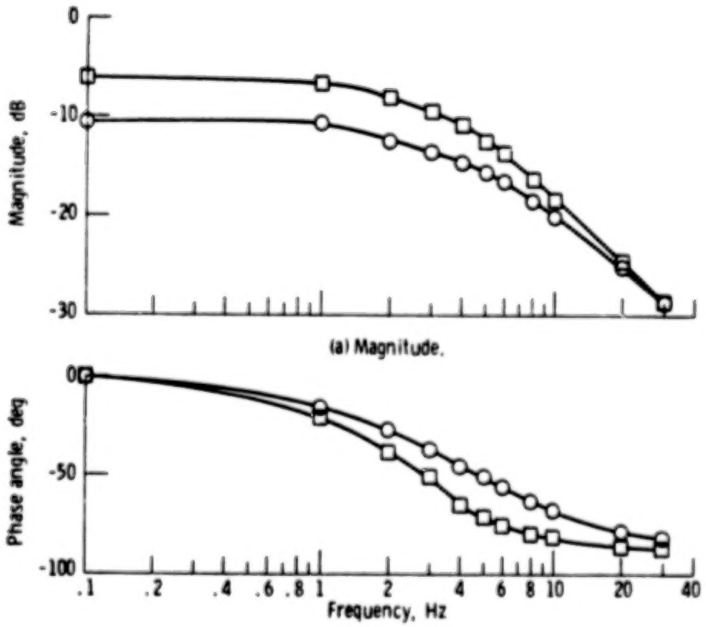


Figure 6. - NH/XMV frequency response.

PERFORMANCE-SEEKING CONTROLS

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INTRODUCTION

Constantly increasing fuel costs justify the investigation of control methods to optimize the performance of aircraft propulsion systems. The task requires a method to trim engine control variables to an optimum condition. Engine control schedules are usually developed during the design and testing stages. However, since perfect engine control matching is time consuming and costly, control schedules are usually less than perfect. More important is the fact that engine-to-engine component variations are normally sufficient to cause the engine to operate at a nonoptimum condition. Also, during the life of the engine, component and sensor degradation can result in a higher fuel consumption to maintain a particular engine thrust.

This paper describes a performance-seeking logic algorithm (PSL) that optimizes the performance of propulsion systems for component and sensor degradations.

PERFORMANCE-SEEKING LOGIC

The objectives of the performance-seeking logic (PSL) algorithm are to monitor the performance of the engine system and to minimize thrust specific fuel consumption (TSFC) while retaining a constant engine net thrust. Engine constraints such as surge margin, speed, pressure, and temperature must be observed. The PSL algorithm was applied to the quiet, clean, short-haul experimental engine (QCSEE) (refs. 1 and 2). This NASA-funded research program was undertaken to develop future STOL engine technology. The QCSEE propulsion system features a high-Mach-number inlet, a variable-pitch fan, and a variable exhaust nozzle (fig. 1). A digital electronic controller and a hydromechanical fuel system are used to implement required control functions. The four QCSEE variables to be controlled are engine pressure ratio (EPR), inlet-duct Mach number, fan speed, and compressor stator angle. The function of the hydromechanical fuel control is to control EPR; fan speed control is achieved by varying the pitch fan angle. A constant inlet-duct Mach number is maintained by varying the exhaust nozzle area in order to reduce aircraft noise problems. The compressor core stator angle is scheduled by the digital controller, which also incorporates the engine control limits. The PSL algorithm only modifies the reference set-point schedules for three of the four engine variables. These include EPR, fan speed, and inlet Mach number. The PSL algorithm does not attempt to modify the compressor stator angle schedules. The hard engine limits are not violated and must be maintained for safe engine operation.

The PSL algorithm was applied to a real-time digital engine simulation. Figure 2 presents a simplified block diagram of the controller, the PSL algorithm, and the engine. The function of this diagram is to illustrate the nominal set-point schedules required to set the control input variables. The PSL algorithm (lower portion of fig. 2) is a secondary controller that operates in conjunction with the normal engine controller. Specific engine output variables can be connected to the PSL block that contains the optimization algorithm to minimize thrust specific fuel consumption subject to selected engine constraints. The output information from the PSL algorithm represents a change from the nominal values for the control input variables. The output of the PSL algorithm modifies the set-point schedules to restore the propulsion system to optimum condition. The PSL algorithm performs system optimization under steady-state conditions.

PERFORMANCE CRITERION

The important consideration in any optimization problem is the selection of a performance criterion. The performance function for the PSL algorithm is

$$J = Q_1 \left(1 - \frac{TSFC}{TSFCN}\right)^2 + Q_2 \left(1 - \frac{FN}{FNNOM}\right)^2 + Q_3 \left(1 - \frac{NL}{NLNOM}\right)^2 + Q_4 \left(1 - \frac{NH}{NHNOM}\right)^2$$

where Q_1, Q_2, Q_3, and Q_4 are weighting factors. The first term identifies the minimization variable TSFC; the remaining terms are the penalty functions. These terms penalize the performance criterion for deviations from their nominal values. The nominal values are dependent on the engine operating condition. Thus scheduling of these nominal values must be considered to make the PSL algorithm effective over the flight envelope. The penalty terms were selected to cause the specific engine variables of the degraded engine system to return to near the design values. By allowing the engine speeds to vary, it could be possible to generate an improved value for TSFC for the degraded engine condition. A thrust measurement must be available for the PSL algorithm. For the actual engine the engine pressure ratio or engine fan speed can be used to generate an equivalent thrust value. A Kalman estimator could also be used for this application. The Q factors provide a weighting capability to increase the effect of a selected parameter. For example, the weighting for net thrust was increased in relation to other weighting factors to assure a nearly constant net thrust.

OPTIMIZATION TECHNIQUES

Several optimization algorithms (refs. 3 to 8) were considered to determine a method that was best suited for the PSL algorithm. The requirement was that the routine be efficient, accurate, and insensitive to initial conditions. The tested methods are as follows:

(1) Fletcher-Reeves - problems encountered due to constraints
(2) Hooke-Jeeves - did not yield minimum value for all cases
(3) Powell - efficient method; no problems encountered
(4) Zangwill-Powell - efficient method; no problems encountered

The various methods determine the unconstrained minimum of multivariable functions. The methods require a unimodal type of function; otherwise several ini-

tial starting values must be considered to assure a true minimum point. The well-known Fletcher-Reeves method is a conjugate gradient method that requires calculation of gradients. Some difficulties with this method were encountered because of the hard engine constraints. The routing has a tendency to become lost during the search process. The Hooke-Jeeves, Powell, and Zangwill-Powell optimization methods are search routines that do not require calculation of the gradients. The Hooke-Jeeves was disregarded since convergence and the minimum value were not achieved for all test cases.

The Powell and Zangwill-Powell methods are essentially similar and generated the minimum values for the various test conditons. The methods converged rapidly and were insensitive to initial conditions. The Zangwill-Powell method was selected since it reflects a departure from the original Powell method in that it tests for linear dependence of the conjugate direction vector. This test assures that a true minimum value will be achieved.

APPLICATION

The effectiveness of the PSL algorithm was evaluated as shown in figure 3. As mentioned previously the digital simulation of the QCSEE engine was used to perform the evaluation phase. An engine component was degraded from its nominal condition with a resultant loss in thrust. For example, the efficiency of the low-power turbine could be reduced by several percentage points. Thrust was then restored by two different methods. A basis for comparison (reference) was then established by a manual method in which the throttle was varied until the net thrust was fully restored to the nominal value of the nondegraded engine. The fan and compressor speeds were scheduled by the throttle and were not constrained. Furthermore the engine control limits were effective for this process. The thrust specific fuel consumption (TSFC) was computed. To evaluate the PSL algorithm, the simulation was returned to nominal and the PSL algorithm was activated. The component degradation was inserted, and the PSL algorithm reoptimized the TSFC and restored thrust to its nominal value. For this case the engine speeds were constrained to their nominal values at the steady-state condition. The two values of TSFC were compared.

The results for several engine component degradations are shown in table I. Typical degradations include loss of efficiency and power requirements for the engine components. With the manual procedure used as the reference, cases B, C, E, and H did not exhibit an improvement for the PSL algorithm. The notations η and P designate a change in efficiency and power requirement. For these malfunctions the pilot can restore the loss of thrust and obtain comparable values of TSFC. For real engine operation the change in component efficiencies and power requirements is a gradual, long-term effect that will be continually corrected by the PSL algorithm. The large perturbations were chosen to accentuate the process and so that we could observe the effectiveness of the "smart" logic. For excessively large variations the algorithm might not correct for the deficiencies unless certain constraints can be relaxed.

The results obtained for conditions A, D, F, and G indicate that the PSL algorithm was able to optimize and generate an improved TSFC over that generated by the manual method. For example, a lower low-pressure-turbine effi-

ciency resulted in a 1.8-percent higher value for TSFC; a higher fan power requirement caused a 1.6-percent higher value of TSFC. Similarly a combination of deficiencies (i.e., A-B, A-D) provided a higher value of TSFC for the manual throttle change. These latter cases imply that the scheduling of the control input variables for the region might not be optimum and thus that a higher fuel flow would be required to restore the nominal thrust. An interesting test was case I, where the thrust could not be fully restored to the nominal value. For the manual case thrust was restored to within 2.5 percent of nominal; the PSL algorithm was able to return the thrust to within 0.8 percent of nominal. These results indicate that if some engine constraints were relaxed and speeds allowed to seek a new value, improved results might be obtained for the PSL algorithm.

Although a limited number of test conditions were demonstrated, it can be deduced that the PSL algorithm can do as well or better than the manual control. Since degradation effects are minimal, accruable, and long term, it is evident that the added secondary controller serves a useful purpose in maintaining optimum system performance and in relieving the pilot of an added burden.

CONCLUSIONS

The objective of the PSL algorithm is to optimize the performance of the propulsion system at a steady-state condition. The major function is to modify the engine control set-point schedules for component degradations in order to restore the nominal net thrust. The results of the study indicate that this task can be achieved with the PSL algorithm. Convergence to the optimum value can be obtained within 60 to 90 seconds, which makes the program acceptable for on-line operation with present state of the art minicomputers.

Several optimization procedures were evaluated; however, difficulties were experienced with the Fletcher-Reeves and Hooke-Jeeves methods. These problems are attributable to the hard engine limits. The selected method was the Zangwill-Powell technique, which offered rapid and accurate convergence. The tests indicate that in most cases the PSL algorithm offers some improvement in thrust specific fuel consumption over the manual throttle.

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TABLE I. - RESULTS OF ENGINE COMPONENT DEGRADATION

[Throttle was adjusted for constant thrust at steady-state condition.]

Case	Effect	Fuel flow - TSFC (PSL improvement over throttle), percent
A	Low-pressure turbine, $\Delta\eta$ = -10 percent	1.8
B	High-pressure turbine, $\Delta\eta$ = -10 percent	No change
C	Compressor power, ΔP = 10 percent	No change
D	Fan power, ΔP = 10 percent	1.6
E	Accessory equipment, ΔP = 100 percent	No change
F	Cases A and B	.6
G	Cases A and D	4.1
H	Cases A, B, C, and E: A and B, $\Delta\eta$ = -5 percent C, ΔP = 5 percent E, ΔP = 100 percent	No change
I	Cases A, B, C, and E: A and B, $\Delta\eta$ = -10 percent C, ΔP = 5 percent E, ΔP = 100 percent	(a)

[a]Nominal values of thrust could not be achieved.

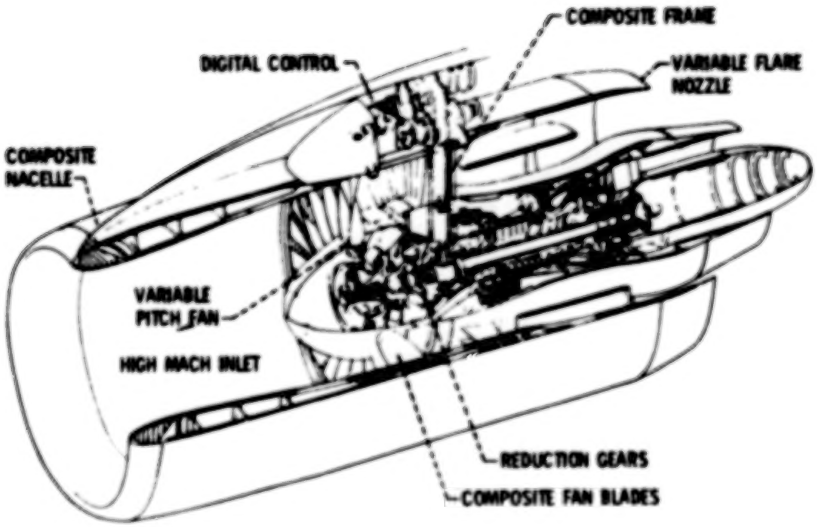


Figure 1. - QCSEE UTW engine.

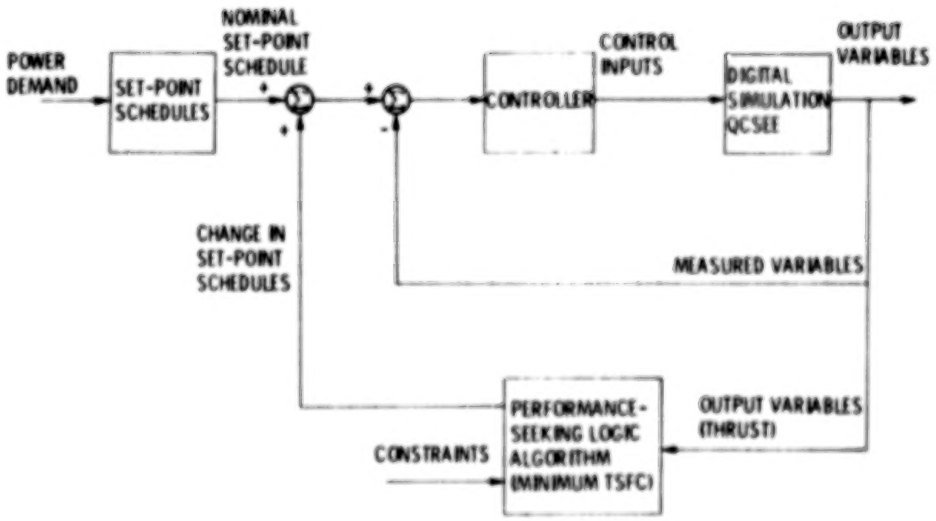


Figure 2. - Block diagram of performance-seeking logic algorithm applied to QCSEE.

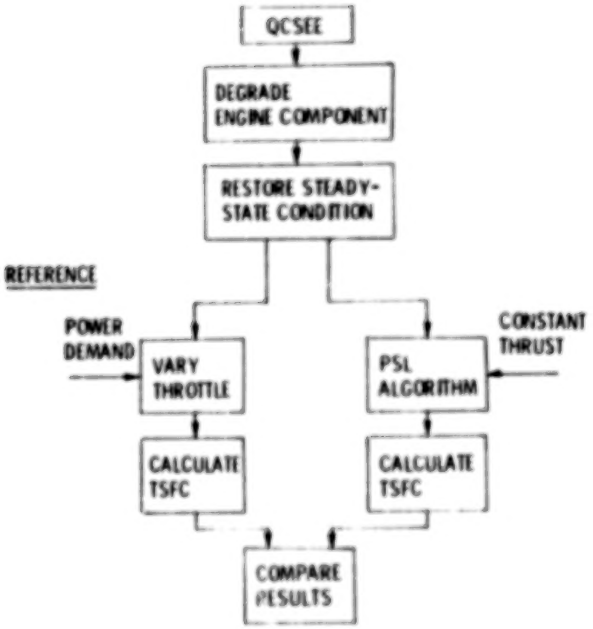


Figure 3. - Evaluation procedure.

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APPLICATIONS OF MULTIVARIABLE CONTROL TO ADVANCED AIRCRAFT TURBINE ENGINES

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ABSTRACT

Aircraft turbine engine propulsion control systems have been the focus of extensive development in recent years. Improvements in all types of engine components have been realized by optimization of materials and configuration. Also, the addition of variable internal geometry has provided the potential for improved response capability without sacrificing efficiency or performance. The penalty for this improved performance potential, however, is a significant increase in engine complexity (additional actuators, sensors, etc.). The subsequent control problem of maintaining strict transient and steady-state performance specifications thus also becomes more complex, forcing attention to more accurate, reliable, and versatile controller implementations. The evolution of such digital multivariable control structures from the F100 program to the ongoing GE JTDE-23 variable-cycle engine program and beyond were presented.

The F100 program was briefly reviewed. This program culminated in the first successful test cell demonstration of a digitally implemented multivariable controller on an advanced turbofan engine. The structure of the controller employed was modular. That is, functional logic elements were implemented as independent blocks of computer code. A feedforward component of control was provided by a transition model that computed constant rate trajectories (state and control) between the current operating point and that requested by a reference-value generator. Disturbances and modeling errors were accommodated by a state-variable regulator that incorporated integral trim on critical variables.

A second-generation controller being developed for the GE JTDE-23 variable-cycle engine was next discussed. It is an extension of the controller used on the F100. The modularity concept has been preserved, but improvements have been made in each functional logic element. Various modes of operation have been included in the reference-value generator. Thus the engine can be trimmed for maximum stability, maximum thrust response, minimum thrust specific fuel consumption, etc. The transition model has also been improved. Rather than constant rate trajectories, approximate optimal time paths are employed. To reduce the sensitivity of the controller to disturbances and modeling errors, the regulator is output feedback (eliminating the need for integral trim). A high degree of fault tolerance has been incorporated in the controller operation.

Finally, near-term achievable advances in the application of multivariable control to advanced aircraft engines were reviewed. Areas being investigated include improvements in fault tolerance and reliability and the integration of advanced computer architectures into the controller design. Other areas include the extension of the controller to the systems level through propulsion-airframe integration and inlet-augmentor-airframe integration.

F100 MULTIVARIABLE CONTROL SYNTHESIS PROGRAM: A REVIEW OF FULL-SCALE ENGINE ALTITUDE TESTS

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SUMMARY

The F100 Multivariable Control Synthesis (MVCS) program was conducted to demonstrate the benefits of linear quadratic regulator synthesis methods in designing a multivariable engine control capable of operating an engine throughout its flight envelope. The program, jointly sponsored by the Air Force Aero Propulsion Laboratory and the NASA Lewis Research Center, encompassed the design, real-time hybrid computer evaluation and full-scale engine testing of a multivariable control for an F100 engine.

This paper reviews the entire MVCS program, with particular emphasis on engine tests conducted in the NASA Lewis Propulsion Systems Laboratory altitude facility. The multivariable control has basically a proportional-plus-integral, model-following structure with gains scheduled as functions of flight condition. The multivariable control logic design is described, along with control computer implementation aspects.

Altitude tests demonstrated that the multivariable control logic could control an engine over a wide range of test conditions. Representative transient responses are presented to demonstrate engine behavior and the functioning of the control logic.

INTRODUCTION

The F100 Multivariable Control Synthesis (MVCS) program was jointly initiated by the Air Force Aero Propulsion Laboratory (AFAPL) and the NASA Lewis Research Center. Its objective was to demonstrate the benefits of using linear quadratic regulator (LQR) synthesis techniques in the design of a multivariable control system for operating a turbofan engine throughout its flight envelope.

The program was divided into three phases. The goal of phase 1 was to design the control logic based on a set of linear operating-point models and to evaluate the control on a digital F100 engine simulation. Systems Control, Inc. (Vt.) (SCI) and Pratt & Whitney Aircraft Group, Government Products Division (P&W GPD) were contracted by the Air Force to conduct this phase. P&W GPD generated the required linear models and defined a set of control criteria upon which the LQR design could be based. SCI's task was to produce the actual multivariable control (MVC) design and to evaluate it on a digital F100 simulation provided by P&W GPD. The goal of phase 2 was to evaluate the control by pro-

gramming it on a control computer and controlling a real-time F100 hybrid simulation. It was NASA Lewis' responsibility to program the hybrid simulation facility. Assuming successful completion of phases 1 and 2, the goal of phase 3 was to demonstrate the multivariable control of an F100 engine in the NASA Lewis Propulsion Systems Laboratory (PSL) altitude facility.

All three phases have now been successfully completed. The results of phases 1 and 2 have been documented in references 1 to 8. This paper describes the results of the phase-3 engine altitude tests conducted by NASA Lewis.

F100 MULTIVARIABLE CONTROL LOGIC DESIGN

The Pratt & Whitney F100-PW-100 engine used in the F100 MVCS program is shown in figure 1. It has five controlled variables: main-burner fuel flow, variable-area exhaust nozzle, variable fan-inlet guide vanes, variable compressor geometry, and compressor exit bleed. Although it is not as multivariable as variable-cycle engines now under development, the F100 exhibits sufficient control complexity to test LQR theory. Since both digital and real-time hybrid F100 simulations exist and an engine was available for altitude testing, the F100 was selected for use in the MVCS program.

In addition to a system dynamic model it was necessary to have a set of control criteria upon which to base an LQR design. The criteria for the F100 engine were formulated by P&W GPD (ref. 1) and can be summarized as follows: Primarily, the control must protect the engine against surge and keep the engine from exceeding speed, pressure, or temperature limits. Airframe-engine-inlet compatibility considerations require that minimum burner pressure limits be accommodated and that maximum and minimum airflow requirements be adhered to at certain flight conditions. The control must insure that engine thrust and fuel consumption are within tolerance for specified engine degradations and for installation effects. It is important that the control accelerate the engine safely, rapidly and repeatably with small overshoots in response to both large and small power level angle inputs. Finally, it must control the engine accurately during flight maneuvers and accommodate disturbances such as afterburner lights.

These controls criteria were translated by SCI into quadratic performance index specifications for use in the LQR design process. The details of the design are contained in reference 2. The design process and the resulting multivariable control structure will be breifly reviewed here. Linear state-variable engine models were generated from the P&W digital simulation at a large number of flight points and power conditions throughout the flight envelope. The engine models' structures were investigated and used to obtain reduced fifth-order linear models. Each linear model is described in terms of its control, state, and output vectors. The variables used by the MVC are shown in figure 1.

Afterburner fuel flow was specifically not considered for control by the MVC; but compressor bleed, not controlled by the current F100 control, was used as an MVC control input. The output vector shown consists of the variables that the five control inputs regulate to establish the steady-state engine operating point.

Using this state-variable model description, SCI designed what is basically a proportional-plus-integral, model-following control having gain matrices scheduled as functions of flight conditions. Figure 2 shows the structure of the resulting MVC design. The reference-point schedules are based on the control schedules used by the current F100 control. They produce reference values for states, outputs, and controls as functions of power level angle (PLA) and the ambient variables PO, PT2, and TT2. The transition control produces smooth, rate-limited transition values x_s, y_s, and u_s between desired reference values so that excessive control error buildup is prevented. The rates are functions of engine face density and power level. The reference-point schedules and transition control comprise essentially the "model" that the model-following control follows.

There are three paths through the control: the feedforward u_s, the proportional path through the LQR gains, and the integral control path through the integral gains. The LQR gain matrix was designed by using standard LQR design techniques. The LQR gains reduce the deviation between the five engine states and their scheduled values and thus alter engine transient response. The integral gain matrix was designed by using a combination of LQR and decoupled pole-placement techniques. The integral trims serve to drive the errors between five selected outputs and their respective reference values to zero in the steady state. Selection of the outputs to be trimmed is performed by the engine protect logic and is described later. Contributions from the three control paths are finally summed to produce the five controller outputs. Because of engine nonlinearity, both LQR and integral gain matrices were scheduled as a function of engine face density and scheduled compressor speed $N2_s$.

The engine protect logic contains schedules that place absolute limits on commanded control variables to assure safe engine operation in the test cell should a sensor or logic failure occur. Also, if an actuator saturates, the logic clamps the associated integrator and eliminates one column from the integral gain matrix to accommodate the loss in degrees of control freedom.

The sensor for the fan turbine inlet temperature (FTIT) is slow. Figure 2 shows an FTIT estimator block that was designed to produce an estimate of the true FTIT and thus compensate for the sensor lag. The FTIT estimate is an engine protection parameter that is used to limit fuel flow at intermediate power (PLA = 83°).

Proper steady-state engine operation is obtained through the action of the integral trims. Fan-discharge $\Delta P/P$ (fan discharge Mach number parameter) is trimmed to its schedule to set the fan operating point. Also, rear compressor variable vanes (RCVV) and compressor inlet variable vanes (CIVV) are trimmed to be on their schedules, and the bleed integrator adjusts to close the bleed in steady state. The other four columns are only used one at a time, depending on flight condition and power level. Usually, fan speed is trimmed to its schedule. However, if a maximum or minimum burner pressure is reached, fan speed is allowed to go off schedule, and the limit is accommodated by switching in the appropriate column. If an FTIT limit is reached, the FTIT column is switched in to allow the integrator to trim fuel flow and area in order to accommodate the limit. An FTIT limit takes priority over a burner pressure limit.

SYSTEM CONFIGURATION FOR ALTITUDE TESTS

Altitude testing of the F100 multivariable control logic was performed in the NASA Lewis PSL altitude facility. Figure 3 shows a system diagram describing the test setup. F100 engine XD11-8 was located in the PSL, but the SEL810B control computer had to be stationed some 1000 feet away in the hybrid computation center. A remote interface unit, located in the PSL control room, received five control command signals from the SEL and sent 24 sensed engine and ambient variables to the SEL. All signals were zero to 10 volts and were transmitted over twisted-pair lines with analog-to-digital and digital-to-analog conversion performed at the computer end.

Five research actuators having electrical inputs had to be used in place of the standard F100 hydromechanical actuators. In addition, a backup control was required, both for control of the engine during startup and to take over control in the event of a computer, sensor, or research actuator malfunction. Fuel flow and RCVV research actuators were modified F100 types, and backup control for each came from the standard F100 control. The research actuators for the other three controls were standard position servos. Nozzle area and bleed backups were simply fixed servo command signals. The electrical backup command for CIVV was generated on an analog computer function generator. In the research mode of operation, afterburner fuel flow (zone 1 only) continued to be controlled normally by the standard F100 control.

The variables sensed by the multivariable control were engine control, state, and output variables as well as PO, PT2, and PLA. Temperature TT2.5 was also sensed, as the MVC used it in calculating the RCVV schedule.

The control of the engine's power lever angle remained in the PSL control room, with an electrical PLA signal sent to the SEL computer. Switching of the control from backup to MVC was controlled in the PSL by the test engineer, who also controlled the abort-to-backup button in case of emergency. To aid the controls engineers, located in the hybrid computation center, a cathode-ray-tube display of real-time engine parameters was provided, along with panel meter displays of key engine variables. A two-way voice link and a one-way control-room television monitor facilitated communications.

During a typical altitude test of the multivariable control, the engine was started on its backup control and the altitude facility adjusted to the appropriate values of PO, PT2, and TT2 for the flight condition desired.

The MVC was allowed to perform its control calculations with all integral trims set to zero and generated a set of five actuator commands. These commands were compared to the five sensed control signals. The integral trims were adjusted until the commanded controls equalled the sensed and then the integrators were clamped. This allowed a smooth transfer from backup to multivariable control. Each of the five control variables was then sequentially switched from its backup to its research actuator. The integral trims were released and the engine was then on multivariable control. Engine control reverted to the backup mode if the computer detected a sensor or actuator failure. At the completion of MVC testing, an abort command initiated either by the SEL

computer operator or by the engine operator put the engine control in backup mode in preparation for engine shutdown.

COMPUTER IMPLEMENTATION

The MVC logic shown in figure 2 was implemented on the Lewis SEL810B control minicomputer. The SEL810B has specifications representing a current flight-type computer with a 24K 16-bit core memory and a 0.75-microsecond cycle time. Other characteristics of the machine are as follows:

(1) Two 16-bit accumulators
(2) Memory specifications -
    24K magnetic core
    0.75-μsec cycle time
    Expandable to 32K
(3) Two's-complement, fixed-point multiply and divide -
    1.5-μsec add time
    4.5-μsec multiply time
    8.25-μsec divide time
(4) Double-precision arithmetic
(5) Infinite indirect addressing
(6) Infinite indexing
(7) Direct memory access
(8) 28-Levels of vectored priority interrupt
(9) 66 Total instructions

Shown in figure 4 is a control timing diagram of the MVC logic used in the PSL tests. In the 12-millisecond update time of the control, the computer performs the control-algorithm control sequencing, sensor-actuator-output failure checks, and research data input and output. The control algorithm and the control sequencing operation were discussed previously.

The sensor failure checks performed by the SEL810B consist of a simple min-max limit check on all sensors and either a delta check or a set-point deviation check. The delta check compares the present value of the sensor to the past value in order to detect erratic signal behavior. The set-point deviation check uses the multivariable control's own set-point schedules and transition logic to generate a modeled value for the sensor. This modeled value is compared with the actual sensed value to determine if the sensor is behaving in an abnormal manner. The actuator checks are made by doing nonlinear simulations for the actuator dynamics in the control computer. The outputs of the simulations are compared with the actuator feedback signals to verify that the actuators are behaving within normal bounds. For the sensor and actuator checks the failure must be present during four consecutive update intervals for the signal to be declared bad. The output checks verify that the difference between the current output and the past output is within some specified tolerance. This allows detection of a possible failure in the arithmetic unit, undetected shift overflows, etc. This check had to be invalid for only one update interval in order to be considered a failure.

The research data input and output functions are performed during the computer's spare time. This spare time occurs when the control is waiting for the

interval timer interrupt after it has finished calculating the update of the control and during the time that the digitizer is sampling the input data. In this spare time an input-output program called INFORM (ref. 9) is run to generate necessary research data. These data can be either transient or steady state. The steady-state data are output in engineering units to a floppy disk. or to the teletype. The transient data can also be output to the disk for later processing or to brush recorders for dynamic real-time data evaluation and debugging. The data output to the floppy disk can be transmitted to a central computer for further processing, plotting, etc.

Table I shows the control's memory requirements. The total amount of software necessary to perform the MVC algorithm is 7787 words. This includes 4091 words of code and 2488 words of schedule and matrix data. The sensor-actuator-output checks add another 1743 words. Therefore a total of approximately 9500 words is necessary to the complete MVC task for the F100 engine. Furthermore the general-purpose input-output and debug package (INFORM) adds 5694 words to the total controls package.

ALTITUDE TEST RESULTS

Transient and steady-state performance of the MVC was demonstrated by testing at six subsonic and four supersonic points. These points were selected to represent the operating envelope of the F100 engine. Steady-state operating line data were taken at all points. In certain regions, airflow and/or burner pressure limits restricted the range of steady-state operation to be close to intermediate (PLA = 83°). A total of 309 individual steady-state data points were taken. Overall, the MVC tracked the reference-point schedules well. FTIT and burner pressure limits were accommodated where required. The RCVV's and CIVV's were held to their respective schedules through the integral trims. The two remaining scheduled variables that determine the steady-state operating point are fan speed and fan-discharge $\Delta P/P$. They were made to track their schedules properly through use of integral trims on exhaust nozzle area and fuel flow. There were, however, some minor problems with area-trim integrator saturation near midpower at some flight conditions, but these could be corrected by further schedule refinements.

Transient performance of the multivariable control was assessed at all flight points. Large PLA transients (idle to 83°, 50° to 83°, 83° to idle, etc.) were run at all points where airflow schedules allowed PLA operation below 83°. Three-degree PLA transients were run to check regulator performance, and cyclic or random PLA sequences were run to verify correct gain scheduling logic operation. In all cases, PLA was changed at the rate of ± 126 degrees per second. Repeatable PLA transient inputs were assured by the use of a programmable function generator to control PLA during transient tests. In all, 93 transients were run on multivariable control. In this paper only three will be presented to demonstrate typical control performance in response to (1) a large PLA input at a low-altitude, subsonic condition; (2) an afterburner light at supersonic conditions; and (3) a simulated flight maneuver.

Figure 5 shows the response of the engine under multivariable control to a PLA snap from 50° to 83° at 10 000 feet, Mach 0.6. Engine dynamic characteris-

tics here are quite similar to those at sea-level static conditions. This transient exercised a number of multivariable control logic functions: transfer from fan-speed trim to FTIT trim, regulator and integrator gain scheduling as a function of compressor speed, FTIT estimation of FTIT, and trimming of nozzle area to set fan-discharge $\Delta P/P$. It can be seen that, before the PLA snap occurred at 0.5 second, fan speed was on schedule. After PLA moved, the transition control generated request values of the state variables (fan and compressor speed and burner and afterburner pressure. Differences between the sensed and scheduled values were fed through the regulator to cause the sensed values to track the schedules. The states responded in a stable, controlled fashion, with little or no overshoot. The FTIT estimate reached the FTIT limit shortly before 1 second. At this point the fuel-flow integrator input error was switched from fan speed to FTIT, and consequently fan speed fell below its scheduled value in steady state.

Fuel flow and the three components that, added together, produced its command are also plotted in figure 5: the scheduled value, the LQR output, and the fuel-flow integrator output. Fuel flow remained close to its scheduled value. The LQR contribution initially increased to reduce negative errors in the state variables. Fuel-flow integrator uptrim was inhibited until the FTIT estimate reached the limit. At this point the integrator introduced downtrim, which reduced fuel flow below its scheduled value. This caused the FTIT estimate to decrease so that in the steady state FTIT was at its limit.

The nozzle area moved both to trim fan-discharge $\Delta P/P$ to its schedule and to reduce state-variable errors during the transient. Figure 5 shows that, before the PLA snap, nozzle area was on a scheduled maximum-area limit; consequently $\Delta P/P$ was lower than its scheduled value. This area limit was introduced during the hybrid evaluation to insure stability for PLA's below about 50°. After the snap began, the LQR nozzle contribution initially increased nozzle area, primarily in response to a negative fan-speed error, and then at about 1.5 seconds decreased nozzle area to null out a negative error in afterburner pressure. The area integrator trim reduced to close the nozzle and cause $\Delta P/P$ to be on schedule at PLA = 83°. The last two traces in figure 5 show the RCVV's, which held quite closely to schedule, and the CIVV's. CIVV's lagged behind the CIVV schedule because of a contribution from the LQR that cambered the CIVV's in order to reduce the magnitude of fan-speed error. In steady state, however, the CIVV integrator overrode any LQR contribution to position CIVV's on schedule. Large transient responses for other flight points were qualitatively similar to the responses shown in figure 5. Exceptions were at high-altitude, low-Mach-number points (45 000 and 50 000 ft at Mach 0.9), where responses were more underdamped than desired. This is possibly due to the effects of unsteady test-cell conditions. Also, a slower-than-normal burner pressure transducer caused the multivariable control responses to be slower than desired for certain large PLA transients. This slow signal caused the standard F100 WF/PB schedule programmed as part of the engine protect logic (fig. 2) to inadvertently limit fuel flow during these accelerations.

Afterburner lights were performed at all flight points to test the ability of the multivariable control to attenuate external disturbances. Feedforward logic is used in the standard F100 control in order to reduce the effect of an

afterburner ignition pulse. Control of the afterburner was specifically excluded from the MVC design. Feedforward logic was not used by the MVC; hence the afterburner pulse acted as a disturbance to the system. Figure 6 shows the results of an afterburner light at a high-altitude supersonic condition (55 000 ft at Mach 1.8). The control rapidly responded to attenuate the afterburner pressure pulse resulting from the light. The results also verify the correct scheduling of LQR and integral gains and reference-point schedules at this supersonic, high-inlet-temperature point. The light occurred at 0.5 second, as shown by the rise in afterburner fuel supply pressure in the top trace. The effect of the light was to cause afterburner pressure to increase and fan speed to drop. Compressor speed remained essentially constant. The FTIT estimate followed the sensed value with an offset of about 8 degrees. During the light the estimate was held close to the limit through integral trim on fuel flow, thus causing the sensed value of FTIT to remain below the limit.

Figure 6 also shows that fan-speed error (and to some extent afterburner pressure error) acted through the LQR area output to initially open the nozzle. At the samt time, fan-discharge $\Delta P/P$ dropped below schedule and caused the area to open until $\Delta P/P$ was back on schedule. The net result was that afterburner pressure was attenuated as desired. There was also some slight control activity on fuel flow as the fuel-flow integrator trimmed to keep FTIT below its limit. The multivariable control successfully attenuated afterburner pressure pulses at all other flight points except for 45 000 and 50 000 feet at Mach 0.9. Here, sensed fan-discharge $\Delta P/P$ did not change sufficiently to allow nozzle trim control to suppress the disturbance. Further analysis of sensed $\Delta P/P$ data in this region is being undertaken.

A total of nine simulated flight maneuvers were performed to test, in particular, gain scheduling and FTIT estimator performance with varying PLA and ambient conditions. Maneuvers included combinations of climbs, dives, accelerations, and decelerations; and the multivariable control performed well in all tests. Figure 7 shows one representative maneuver, an acceleration at a constant 10 000-foot altitude. Actual pressure altitude varied from about 8500 to 11 000 feet during the transient, and Mach number increased from 0.6 to 0.9 in about 15 seconds. Inlet temperature could not be changed, so the initial condition was standard day and the final condition was 40 degrees F colder than standard day. The PLA was increased manually from 65° to 83° in about 5 seconds. Figure 7 shows compressor speed making a controlled transition with a slight overshoot. Fan speed tracked its schedule with a slight overshoot. Figure 7(b) shows that at about 4 seconds the FTIT estimator reached the limit and the fuel-flow integrator ceased trimming on fan-speed error and downtrimmed fuel to keep FTIT below its limit. In steady state, FTIT held to the limit within 5 degrees F. Finally, figure 7(b) shows that the exhaust nozzle area closed down to keep fan-discharge $\Delta P/P$ on schedule as desired. In summary, the multivariable control produced a well-controlled transition of engine power setting with varying ambient conditions.

CONCLUSIONS

The objective of the F100 Multivariable Control Synthesis program was to demonstrate that a control that would operate a modern turbofan engine over its

flight envelope could be designed by using linear quadratic regulator (LQR) design methods.

The multivariable control was tested while controlling an F100 engine at 10 flight points in an altitude facility. The control exhibited good steady-state performance, that is, the ability to hold engine trim variables on schedule at all flight points.

Good transient performance was demonstrated at almost all flight points. The integral trims successfully accommodated FTIT limits and low burner pressure limits where required. The control attenuated afterburner pressure pulses occurring during afterburner lights at all but two flight points. At supersonic points, where operation was permitted only at intermediate and above, excellent suppression of afterburner disturbances was observed. A number of flight maneuvers were performed to check the control's performance with simultaneously varying PLA and ambient conditions. The control tracked reference-point schedules well and accommodated all limits.

Sensor and actuator failure detection logic was incorporated into the control for altitude tests and functioned well in conjunction with a backup control. All the control logic was programmed in 9.5K of core, using a 12-millisecond computer cycle time. These computer requirements are within the capabilities of present-generation computers envisioned for use as engine-mounted digital controls.

It is concluded that LQR-based control design techniques can be successfully used to design digital engine controls. The systematic, structured approach used in the F100 MVC design has much to offer in the design of controls for next-generation airbreathing engines.

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TABLE 1. - CORE REQUIREMENTS FOR MVC PROGRAM

MVC Control Algorithm:		
FTIT Estimator		309
Set Point Schedules		618
Gain Control		834
Transition Control		632
Integral Control		783
LQR Control		347
Engine Protection		198
Function Generation		370
	Total	4091
Block Data:		
Schedules		1752
Matrices		736
	Total	2488
Failure Detection Logic:		
Sensor Checks		1169
Actuator and Output Checks		574
	Total	1743
Control Executive		1208
	Grand Total	9530
General-Purpose Input-Output and Debug		5694

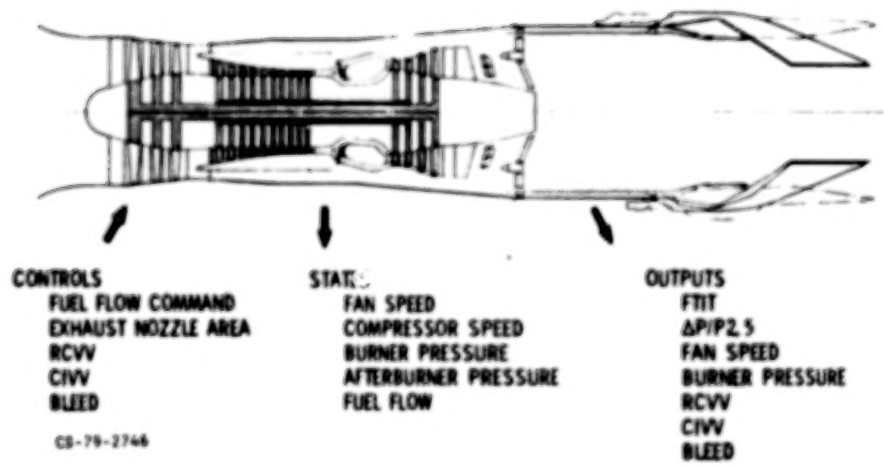


Figure 1. - F100 engine variables used for multivariable control.

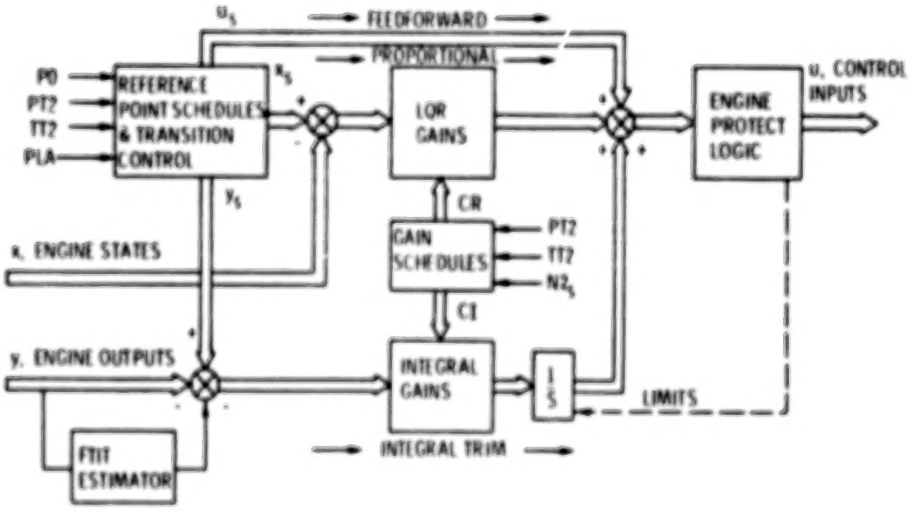


Figure 2. - Structure of F100 multivariable control.

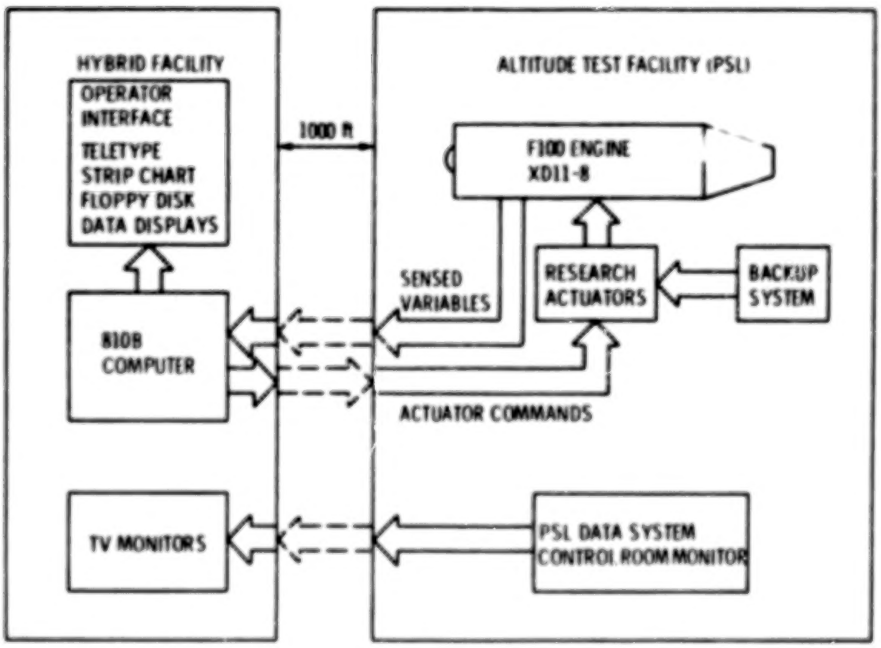


Figure 3. - Control system schematic for altitude tests.

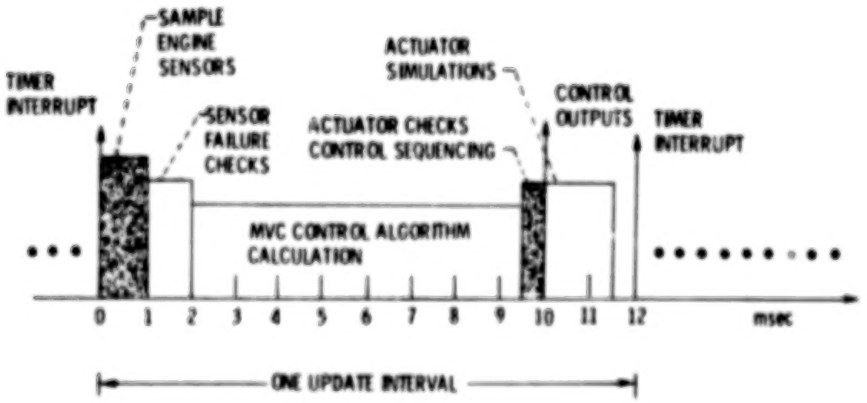


Figure 4. - MVC control timing diagram.

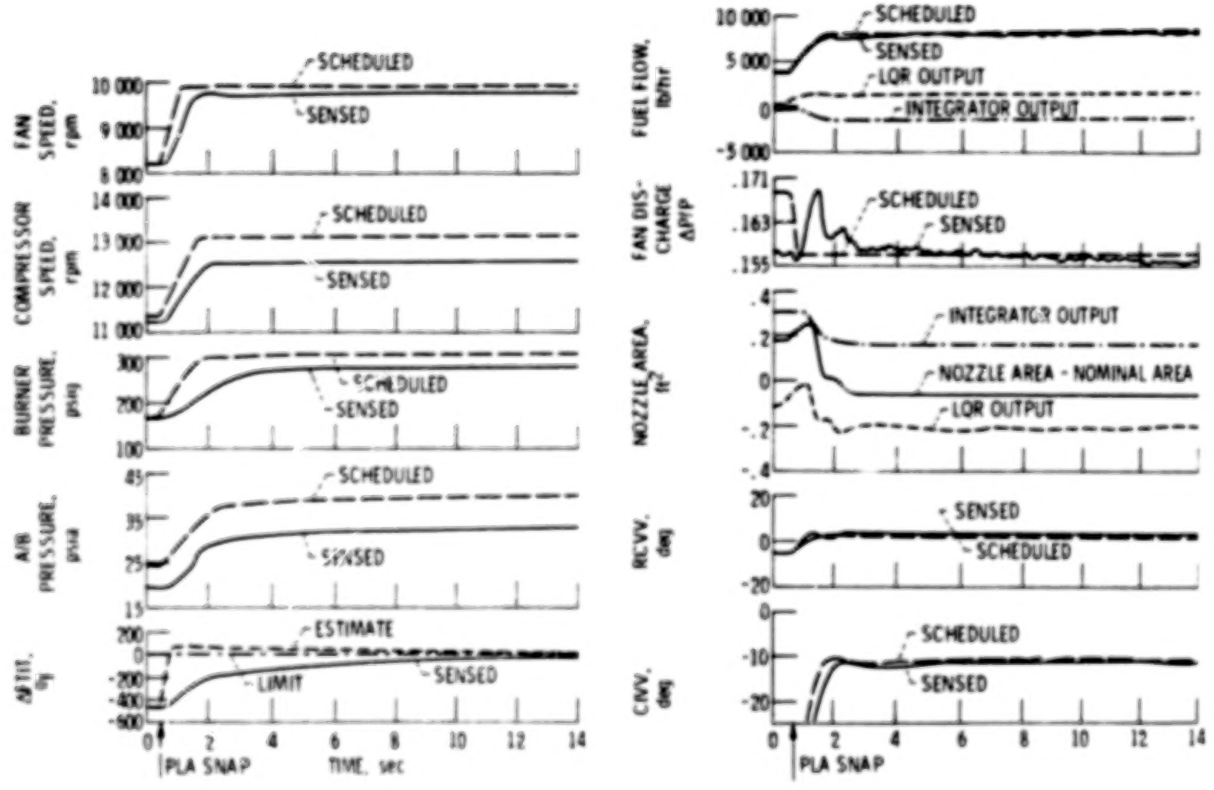


Figure 5. - Typical F100 multivariable control performance in large PLA transient. Altitude, 10 000 ft; Mach number, 0.6; 50° to 83° PLA snap.

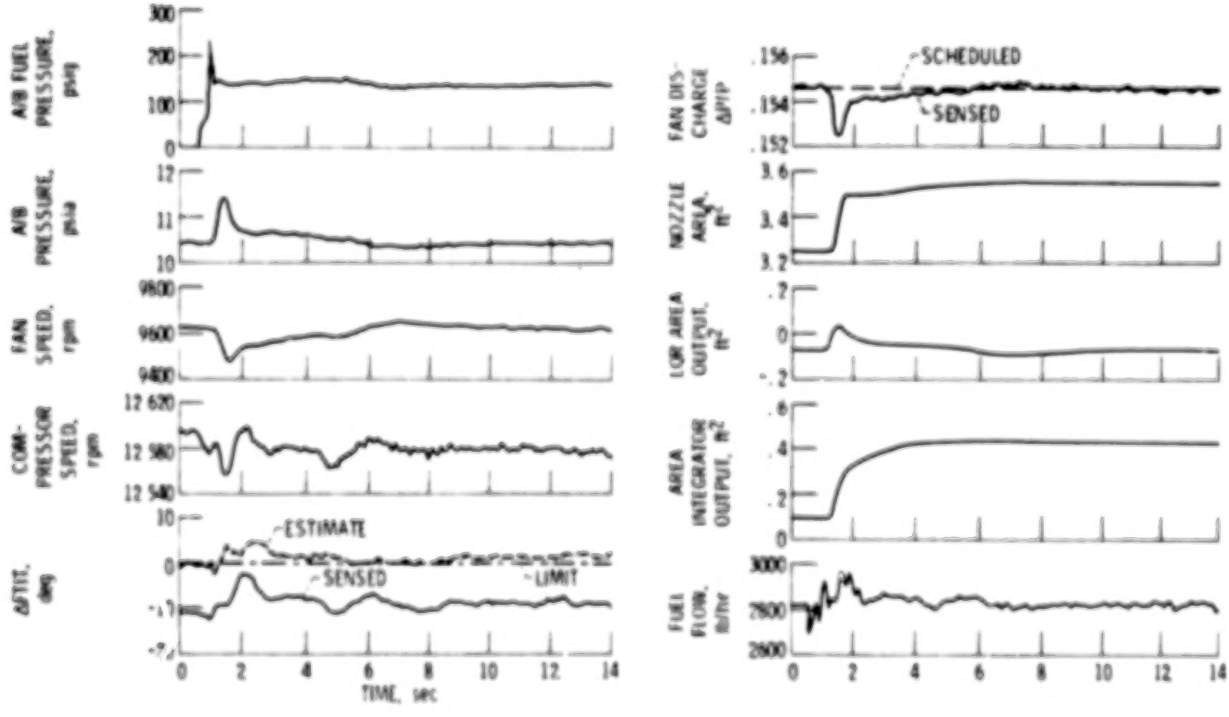


Figure 6. - Typical afterburner transient at supersonic conditions. Altitude, 55 000 ft; Mach number, 1.8.

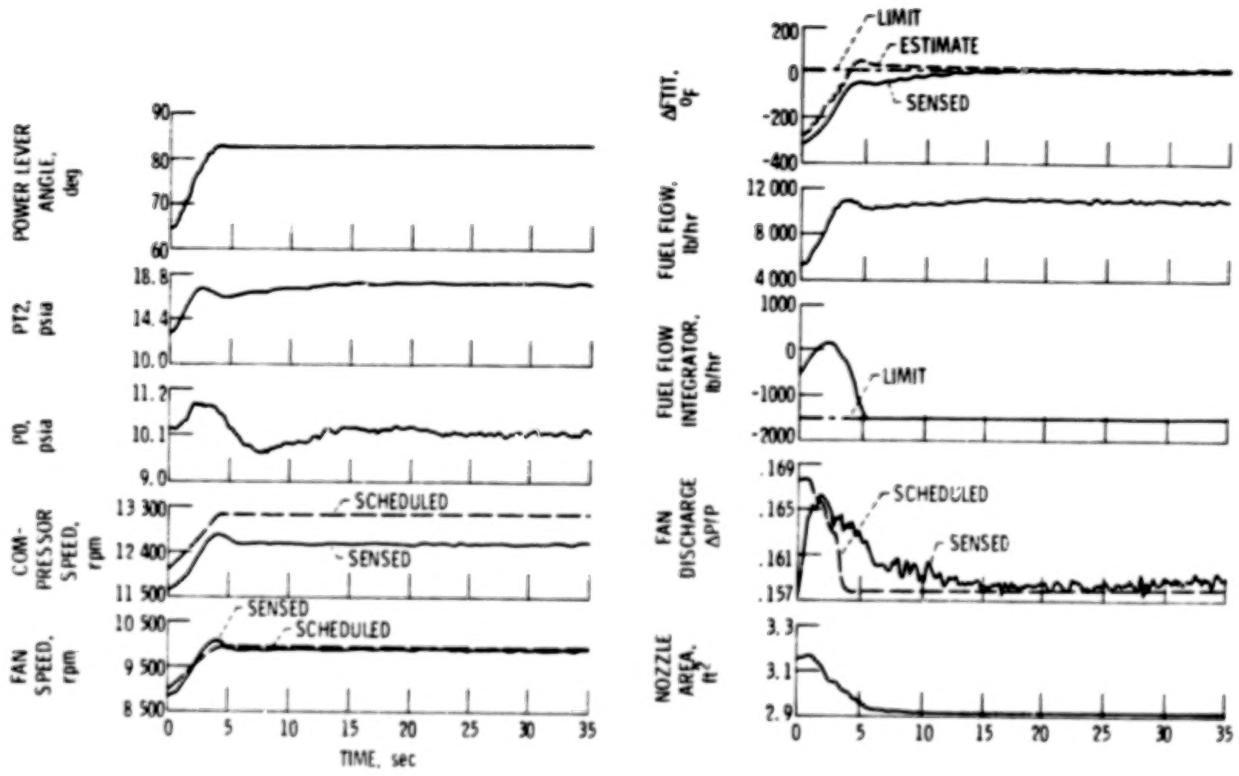


Figure 7. - F100 flight maneuver simulated in altitude facility. Altitude, 10 000 ft; initial Mach number, 0.6; final Mach number, 0.9; initial inlet temperature, standard day; final inlet temperature, 40° F (cold-day conditions).

DESIGN OF A MULTIVARIABLE INTEGRATED CONTROL FOR A SUPERSONIC PROPULSION SYSTEM

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SUMMARY

A study was conducted of an inlet/engine/nozzle integrated control mode for the propulsion system of an advanced supersonic commercial aircraft. This study showed that integration of these control functions can result in both operational and performance benefits for the propulsion system. For example, this integrated control mode may make it possible to minimize the use of inlet bypass doors for shock position control. This may be of benefit to the aircraft as a result of minimizing: (1) bypass bleed drag effects; (2) perturbations to the aircraft resulting from the side thrust effect of the bypass bleeds; and, (3) potential unstarts of the inlet. A conceptual integrated control mode was developed which makes use of many cross-coupling paths between inlet and engine control variables and inlet and engine sensed variables. A multivariable control design technique based upon Linear Quadratic Regulator (LQR) theory was applied to designing the feedback gains for this control to allow a simulation evaluation of the benefits of the integrated control mode.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is engaged in studies and advanced technology programs for future supersonic commercial aircraft, with emphasis on improving environmental and performance characteristics. As part of this overall program, Pratt & Whitney Aircraft (P&WA) is conducting advanced propulsion technology programs.

The time frame for these programs is consistent with advanced technology projections that would permit a U.S. entry into the commercial supersonic aircraft market by the late 1980's or early 1990's.

The work presented in this paper was accomplished during a brief study as part of a NASA-sponsored study conducted by the Lockheed-California Company, with P&WA Commercial Products Division as sub-contractor.[1]

VARIABLE STREAM CONTROL ENGINE

Results from broad parametric studies and refined integration studies indicate that the Variable Stream Control Engine (VSCE) has the greatest potential for future supersonic transports.[2,3] This VSCE concept employs variable components and a unique throttle schedule for independent control of two flow streams to provide reduced jet noise at take-off and high performance at

both subsonic and supersonic cruise. Figure 1 shows the basic arrangement of the major engine components in a twin spool configuration similar to a conventional turbofan engine. The low spool consists of an advanced technology, multi-stage, variable geometry fan and a low pressure turbine. A variable geometry compressor driven by an advanced single-stage high temperature turbine makes up the high spool. The primary burner and the duct burner require low emissions, high efficiency combustors. A two stream, concentric, annular (co-annular) nozzle design with variable throat areas in both streams and an ejector/reverser make up the exhaust system.

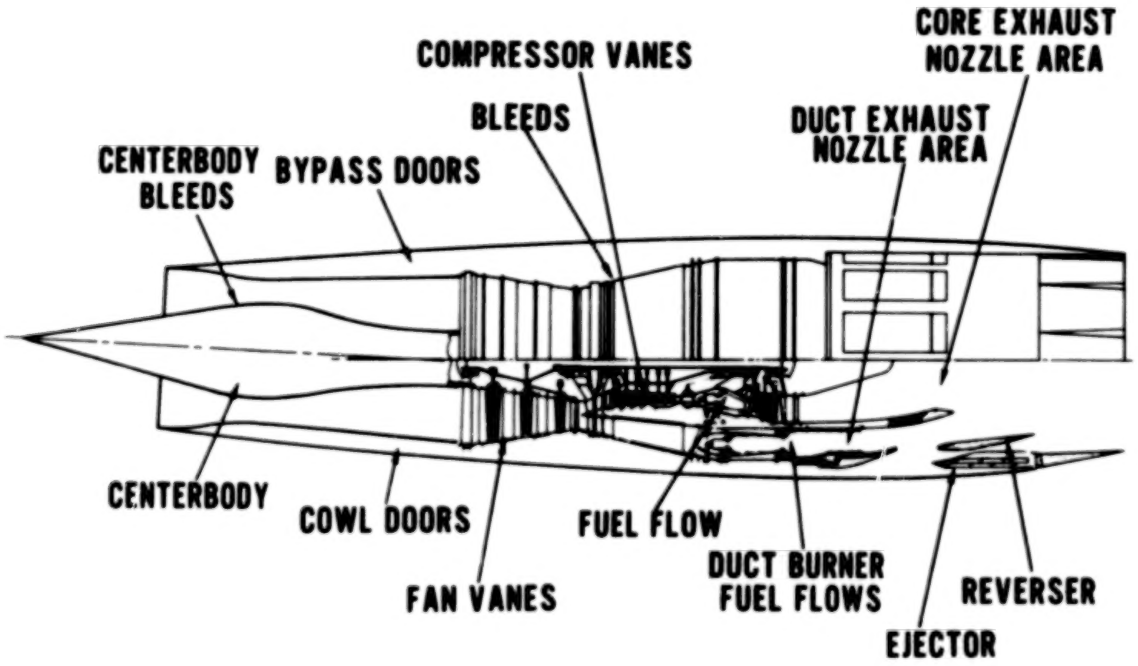


Figure 1 Propulsion System, Incorporating a Variable Stream Control Engine (VSCE), for an Advanced Supersonic.

Supersonic Inlet

The supersonic inlet for the VSCE will be either an axisymmetric configuration with a translating or collapsible centerbody, or a two-dimensional design with variable walls. Auxiliary inlet doors and bypass doors are included to satisfy off-design and transient operating conditions. During supersonic operation, the primary control requirement for the inlet is to fix the shock position at a location downstream of the throat. Varying the internal geometry, such as translating the centerbody position, varying the bypass doors and matching the engine airflow with the inlet flow rate requires coordination. This will allow optimum positioning of the shock for maximum pressure recovery while minimizing inlet spillage and bypass flow and preventing instability such as unstart and buzz.

Engine

Modulating engine airflow to match inlet airflow is important for optimizing installed performance. Selected rating parameters, such as rotor speeds and/or engine pressure ratio, are programmed into the control system to provide the specific thrust, airflow, and temperature ratings at critical operating conditions that result in the desired performance and environmental benefits.

The VSCE fan incorporates variable camber inlet and exit guide vanes. The compressor has several rows of variable stators. Accurate control of these variable geometry components is required to optimize performance over the flight envelope while maintaining stability margins.

The advanced main burner and duct burner have staged combustion systems which require accurate and independent control of fuel flow to each stage to obtain the efficiency and emissions benefits associated with these burner designs. The control system must also provide smooth light-off, stage-to-stage transfer during transient operation, and modulated total fuel flow in each burner stage to obtain the desired power settings.

Nozzle/Reverser

Continuous and independent modulation of both the primary and duct stream nozzle areas is required in conjunction with the engine control variables to provide the desired engine and nozzle operating characteristics. Control of the actuated ejector doors and the thrust reverser must also be provided.

INTEGRATION

Operation and performance of the VSCE propulsion system is a function of the interactions between the inlet, engine, and nozzle. Basic interaction effects are represented in figure 2, and individual performance factors for the inlet, engine, and nozzle are shown in figure 3. Since the integrated propulsion system is affected by all of these interactions and performance factors, it is apparent that an integrated control system is required not only to optimize individual component performance, but also to trade between engine components.

An integrated control can allow closer operation to compressor surge limits to improve compressor efficiency and pressure ratio during steady state operation, and utilize reset logic to accommodate inlet distortion effects or engine transients. Another integration approach is to use engine variables to control the inlet shock position, and thereby minimize the use of drag-inducing bypass doors.

Integration must also be provided between all four propulsion systems and between the aircraft control system. This is required to provide optimum overall aircraft performance and to provide operational reliability and safety by minimizing the possibility of inlet unstarts as a result of aircraft maneuvers. In addition, if an inlet should unstart, the impact on aircraft con-

trollability would be minimized. Therefore, a control system is required which not only provides the propulsion system control function, but can also provide these integration functions.

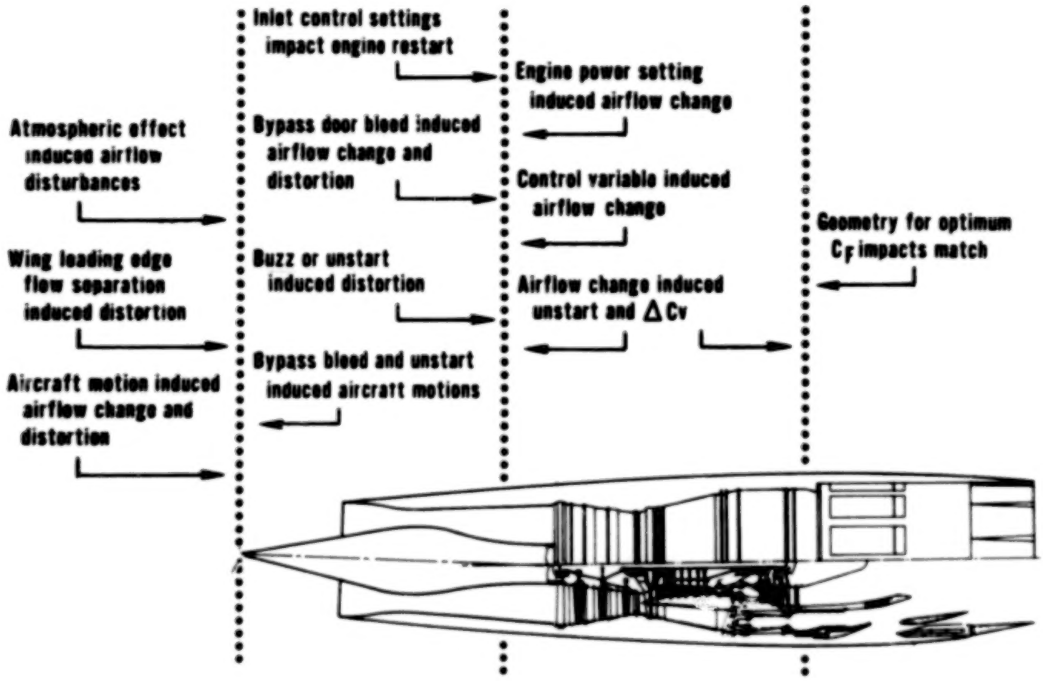
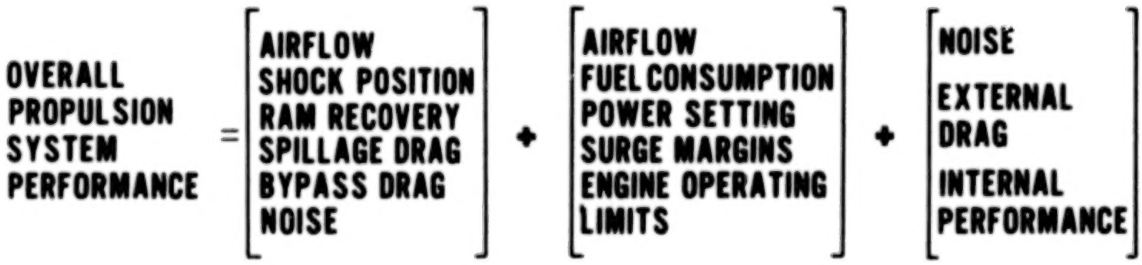


Figure 2 Propulsion System Interactions



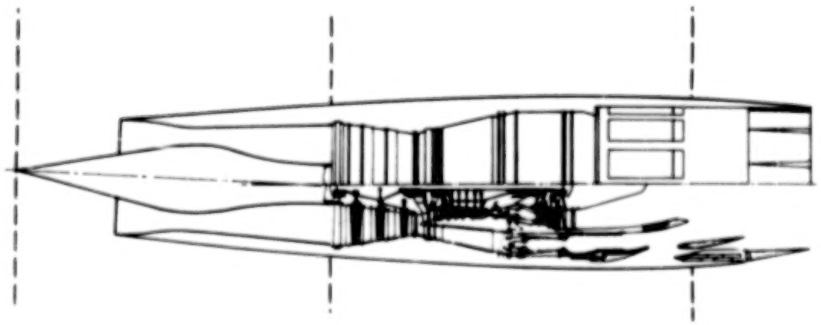


Figure 3 Propulsion System Performance Factors

Integration benefits and inlet/engine/nozzle control function integration approaches were evaluated under the conceptual integrated control study,(1) discussed previously. The integration benefits identified in this study are summarized in table 1.

TABLE I - CONTROL INTEGRATION BENEFITS

- Maximize steady state and transient performance
- Minimize inlet unstarts and engine surge during maneuvers
- Minimize occurrence of buzz
- Minimize use of drag-inducing inlet bypass doors
- Improve aircraft handling qualities
- Maximize operational safety

INTEGRATED CONTROL MODE

Given the individual control requirements for the inlet and VSCE, and integration requirements and approaches, a conceptual integrated control mode was developed. The resulting control mode, shown in block diagram form in figure 4, represents a fully integrated mode in that all anticipated significant cross-coupling loops, both within the engine and between engine and inlet, have been included. Full authority integrators were selected for main burner fuel flow (WFE), compressor bleeds, and bypass doors. Trim integrators, whose output add to steady state reference or correlation schedules, were selected for fan inlet guide vane (FIGVA), compressor stator vanes (CSVA), core nozzle area (AJE), and duct nozzle area (AJD). The use of integrators on each control variable was selected to provide accurate control to the desired propulsion system ratings.

Design and evaluation of control loop gains and dynamic compensation for such a control mode required development of a dynamic simulation of the VSCE engine and the supersonic inlet. The engine simulation consisted of detailed nonlinear dynamic representations of each engine component available from P&WA's simulation system. The inlet simulation selected was based upon a simulation technique developed at the NASA Lewis Research Center, as described in Reference 4. This simulation technique is based upon a linearized mathematical analysis of inlet dynamics and, as such, in only valid for small transient perturbations about the operating point. However, this limitation is acceptable for analysis of integrated control response since (1) engine operation at supersonic conditions is limited to a fairly linear range and, (2) it is desirable to maintain accurate control of shock position (i.e., only allow small variations from the desired shock position) so that inlet operation will also be limited to a fairly linear range.

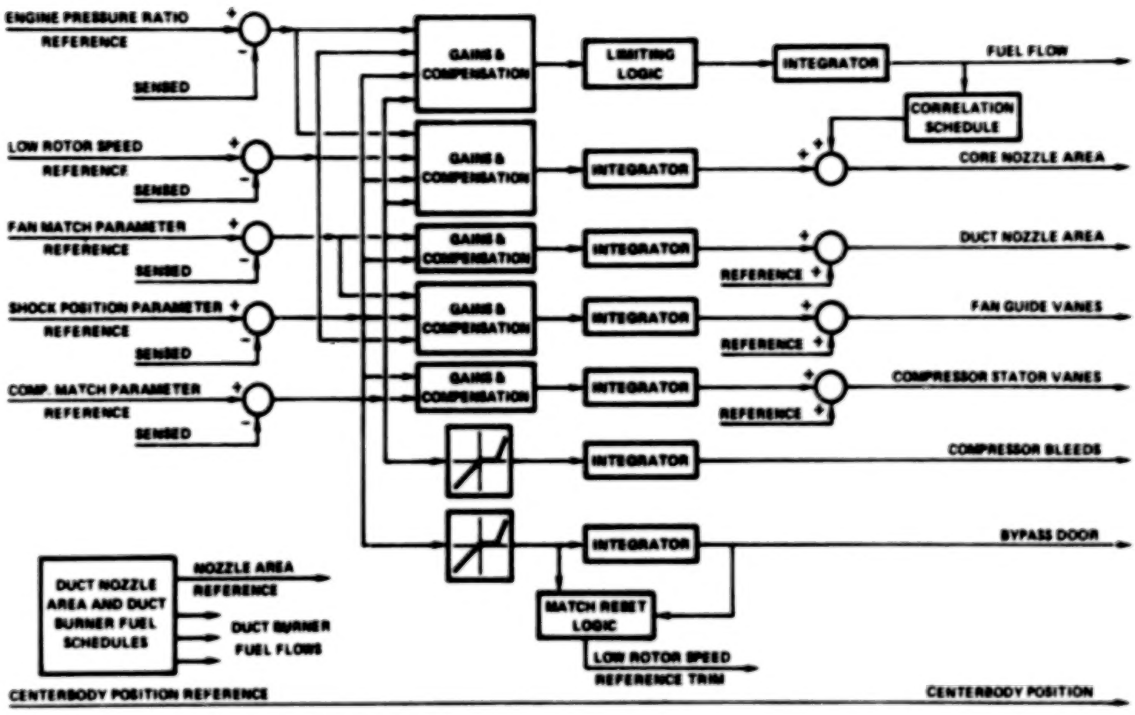


Figure 4 Conceptual Integrated Control Mode

A schematic of an ideal mixed-compression inlet is shown in figure 5. The cross-sectional area variation of the inlet is approximated by constant area sections to minimize the complexity of the resulting simulation. For each duct section chosen, the constant area approximation and a linear analysis of the compressible flow equations result in one-dimensional wave equations representing that section. These wave equations are used to represent both the supersonic and subsonic flow regions. The supersonic and subsonic flow sections are then coupled by linearized equations which relate normal shock, position to adjacent parameters. A linearized equation is also developed for bypass flow, assuming choked flow through the bypass door. Finally the linearized inlet simulation is mated with the nonlinear engine simulation to provide the exit conditions of the inlet.

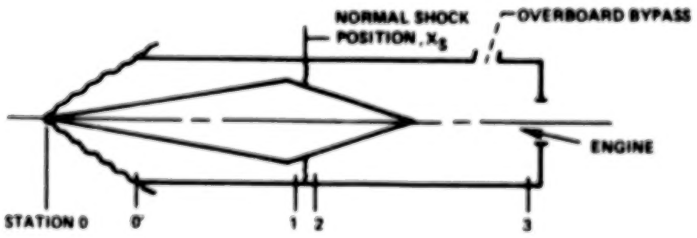


Figure 5 Idealized Mixed Compression Inlet

INTEGRATED CONTROL DESIGN APPROACH

A multivariable control design technique, based on Linear Quadratic Regulator (LQR) theory, was applied to the design of the integrated control mode for the inlet/engine. This technique provides a systematic procedure for designing all cross-coupled loops that are employed in an integrated control mode and assures advantageous use of these cross-coupling effects. Since the LQR multivariable control design technique is a linear technique, the nonlinear equations representing the engine must be linearized and combined with the linear equations representing the inlet. Accomplishing this required definition of the state, control and output variables for the engine and inlet. Generally, it is not desirable to include every state variable in the engine since this can result in an unnecessarily complex control system; i.e., the LQR technique determines control feedback gains from every state variable selected to represent the system. A more effective approach is to recognize the frequency range over which active control is really desired, or possible, and simplify the state variable representation to include only those states associated with engine dynamics in this frequency range.

Based on such considerations, the state, control and output variables shown in table II were selected for the inlet/ engine representation. Even

TABLE II - STATE, CONTROL, AND OUTPUT VARIABLES

X - STATE VARIABLES	U - CONTROL VARIABLES	Y - OUTPUT VARIABLES
X1 - LOW ROTOR SPEED	U1 - MAIN BURNER FUEL FLOW	Y1 - LOW ROTOR SPEED
X2 - HIGH ROTOR SPEED	U2 - CORE EXHAUST NOZZLE AREA	Y2 - HIGH ROTOR SPEED
X3 - MAIN BURNER PRESS.	U3 - DUCT EXHAUST NOZZLE AREA	Y3 - ENGINE PRESS. RATIO
X4 - CORE STREAM EXHAUST PRESS.	U4 - COMPRESSOR STATOR VANES	Y4 - NORMAL SHOCK POSITION
X5 - DUCT STREAM PRESS.	U5 - FAN STATOR VANES	Y5 - FAN PRESS. RATIO
X6 - NORMAL SHOCK POSITION	U6 - INLET BYPASS DOOR AREA	Y6 - COMPRESSOR PRESS. RATIO
X7 - INLET SUBSONIC SECTION TEMP.		Y7 - INLET SUBSONIC SECTION PRESS.
X8 - INLET SUBSONIC SECTION PRESS.		Y8 - HIGH TURBINE INLET TEMP.
X9 - INLET SUBSONIC SECTION AIRFLOW		Y9 - THRUST

though all of the inlet state variables are associated with high frequency dynamics, it is necessary to include several of them since control of the shock position requires relatively high frequency response control loops. The inlet state variables associated with the supersonic flow section were eliminated since it was found that feedback of these variables did not contribute significantly to effective control action. The first six output variables were selected to be consistent with the reference variables shown in the conceptual control mode in figure 4.

Using these state, control and output variables the inlet/ engine simulation was linearized at a supersonic flight condition corresponding to an altitude of 16,800 m (55000 ft) and a Mach number of 2.3. This linearization resulted in a state variable representation of the system consisting of the following two matrix equations:

$$\delta \dot{X} = A\,\delta X + B\,\delta U$$

$$\delta Y = C\,\delta X + D\,\delta U$$

The next step in the LQR control synthesis procedure is to define a performance index as a measure of the goodness of the control effectiveness. A quadratic performance index of the following form is required for the LQR synthesis technique to solve the "output regulator" problem.

$$\text{Performance Index} = J(\delta U) = \int_0^{\infty} \left[\delta Y^T Q\, \delta Y + \delta U^T R\, \delta U \right] dt$$

Minimization of this performance index results in "optimal transient performance" as determined by the selected values in the Q and R weighting matrices on the output and control variables, respectively. For example, placing a high weighting on shock position will improve control regulation of shock position. With the performance index defined, the "output regulator problem" is solved by solving the matrix Riccati equation for the steady state value of K.

$$-\dot{K} = KA + A^T K - G^T \hat{R} G + C^T Q C$$

where $\hat{R} = R + D^T Q D$

and $G = \hat{R}^{-1} (D^T Q C + B^T K)$

The matrix G is the matrix of feedback gains from each state variable to each control variable.

Referring back to figure 4, it can be seen that integrators are desired on each control variable to maintain zero errors between reference and sensed engine variables during steady state operation. Note that the reference variables for fan match, compressor match and shock position were replaced with fan

pressure ratio, compressor pressure ratio and actual normal shock position for this study. These integrators were accommodated by including them as additional state variables along with the inlet/engine state variables, and solving the matrix Riccati equation for the control feedback gains from the complete set of states. This approach results in a solution for the G matrix which can be broken down into a G1 matrix for the inlet/engine states and a G2 matrix for the control integrators as shown in figure 6.

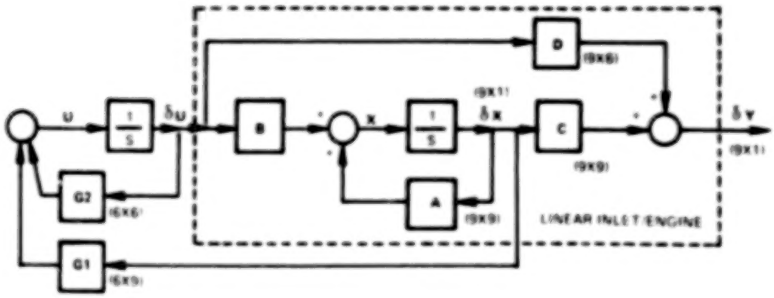


Figure 6 Solution of the Matrix Riccati Equation Determines the G1 and G2 Feedback Gain Matrices from the Inlet/Engine and Control State Variables

The resulting control mode structure is not equivalent to that shown in figure 4. To obtain this structure requires a transformation of the control gain matrices G1 and G2 to the new matrices H, L1 and L2 operating on the output variables Y. Defining the differentials δU and δY as

$$\delta U = U - Uref$$

$$\delta Y = Y - Yref$$

allows implementation of the control system, as shown in figure 7, on a nonlinear inlet/engine simulation for evaluation of small perturbation response at the selected operating point.

The L2 gain matrix is required if the number of state variables is larger than the number of control variables. This can be seen more clearly by considering the summary of the manipulations discussed above. First, the control design procedure determines a control feedback gain from every state variable to every control variable; i.e., the G matrix or the G1, and G2 matrices. Then a set of independent output or observed variables (which can be sensed), equal in number to the number of state variables, is selected to replace the state variables; i. e., the set of state variables, selected for convenience of analysis, may not all be easily measured or may not be equal to the reference variables desired for closing the integral control loops. In this integrated control mode, six reference variables are selected for driving the control integrators to obtain the desired steady state operating point. Thus, the first six output variables must be the same as the six reference variables. This in turn allows the manipulation of the control gain matrices into the structure shown in figure 7 with the L1 and H matrices acting on the first six output error terms. The L2 matrix then operates on the leftover output variables.

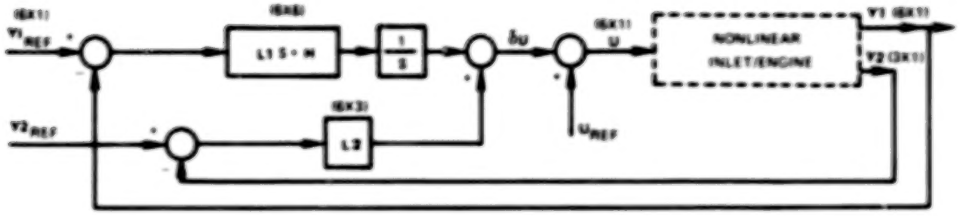


Figure 7 Transformation of the Control Mode Structure to Integral and Proportional Control Paths

If the key inlet/engine variables have been chosen for the first six closed loop control paths, then many of the remaining paths working through the L2 matrix will probably be insignificant and be able to be ignored. If all of these paths can be ignored, then the control mode structure reduces completely to that desired in figure 4. This complete process of mode structure modification and elimination of insignificant gain terms was not carried out during this brief study. A partial transformation of the gain matrices was made, as shown in figure 8, which feeds back the first six output variables for forming the integrator error terms, but retains the remainder of the feedbacks from the inlet/engine state variables. All simulation runs were then made with all elements of the gain matrices retained.

INTEGRATED CONTROL TRANSIENT PERFORMANCE

The LQR control design technique was used to define the feedback control gains, previously discussed, at the 16800 m (55000 ft) altitude, 2.3 Mach number flight condition for the fully integrated control mode. These gains were then implemented on the nonlinear inlet/engine dynamic simulation, as indicated in figure 8, to evaluate small perturbation transients about the steady state operating point. A non-integrated control mode was also designed for comparison with the integrated control mode in order to evaluate operational benefits associated with the integrated concept. This non-integrated control was developed by applying the LQR control design technique to determine the feedback control gains for the engine by itself. Then a single-input, single-output control loop was designed for the inlet to control shock position with inlet bypass doors.

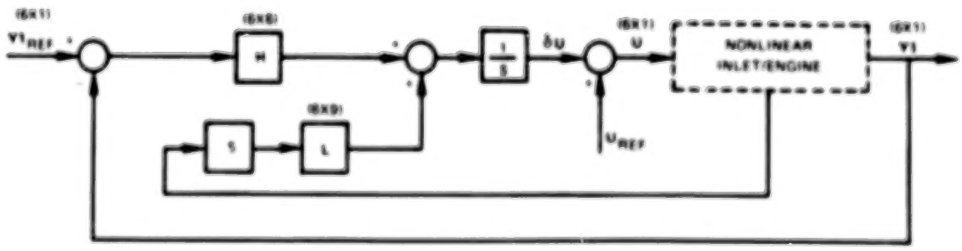


Figure 8 Partially Transformed Control Mode Structure Used for Transient Evaluations

Two types of small perturbation transients were evaluated on the dynamic simulation with the integrated and non-integrated control modes. The first consisted of a 1 percent pulse in ambient pressure of 0.04 second duration to simulate an external disturbance such as a wind gust. The second consisted of a step change in duct burner fuel flow to simulate a duct burner light-off. For this study, it was also assumed that all state variables including shock position were directly measurable.

Transient plots of shock position and inlet bypass door area for the pressure perturbation transients for both control modes are shown in figure 9. For both the integrated and non-integrated control modes the deviation in shock position towards unstart was approximately the same. The implication is that the integrated control mode is not providing any better control of shock position than the non-integrated control. In fact, the integrated control results show bypass door area moving more than in the non-integrated control case to result in the same quality of shock position control. This is theorized to result from the manner in which the engine is being controlled in both cases.

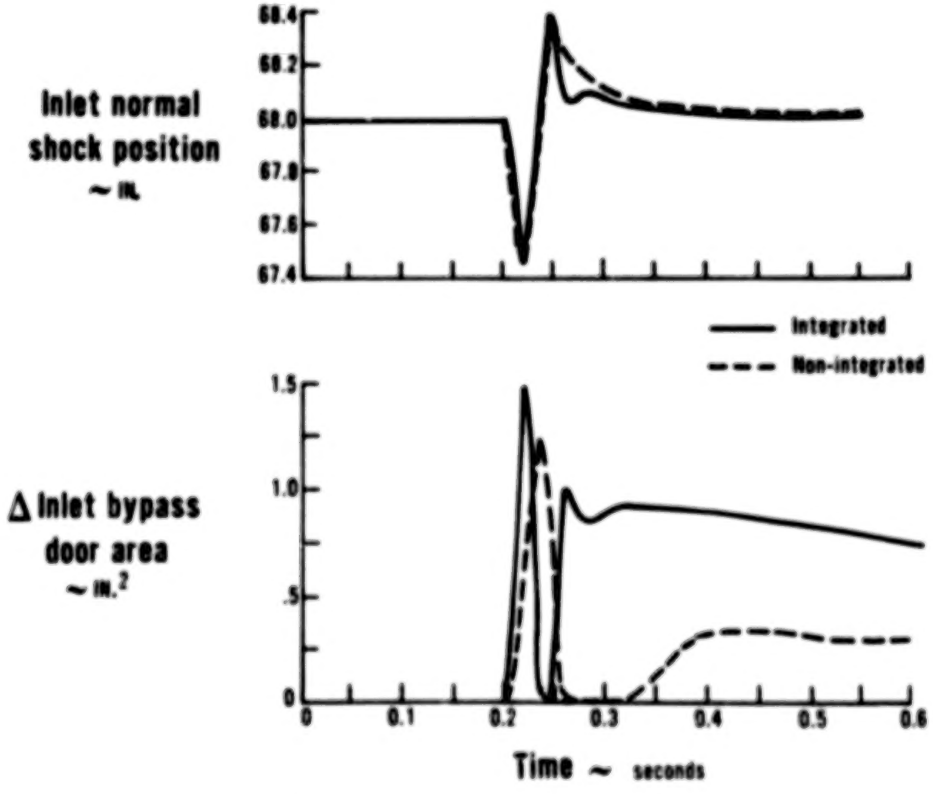


Figure 9 Transient Response to an Ambient Pressure Pulse

Referring back to figure 4, it is seen that the reference parameters for the engine, i.e., the first six output variables, are such that regulating to these variables results in accurate control of engine corrected airflow. Thus, the engine control portion of both control modes responds rapidly to changes in ambient pressure since this has an immediate effect on the engine reference

variables. The result is rapid movement of engine control variables to restore corrected airflow operation. This, in turn, contributes directly to minimizing shock position movement.

The fact that the integrated control mode made more use of the bypass door area would imply that the engine control portion of the integrated mode was not as well tuned as the engine control for the non-integrated control mode. In other words, the weighting gains in the performance index would have to be changed in the design procedure for the integrated control mode to reduce its dependence on bypass doors. These iterations of the control design were not carried out during this study.

Results of the duct burner light-off transients for both control modes are shown in figure 10. The integrated control mode results in less movement of shock position with less use of bypass doors than does the non-integrated mode. These results indicate that there is a potential benefit of an integrated control mode in terms of minimizing use of the inlet bypass doors for shock position control.

To evaluate this potential benefit further would require additional analysis of both the integrated and non-integrated control modes.

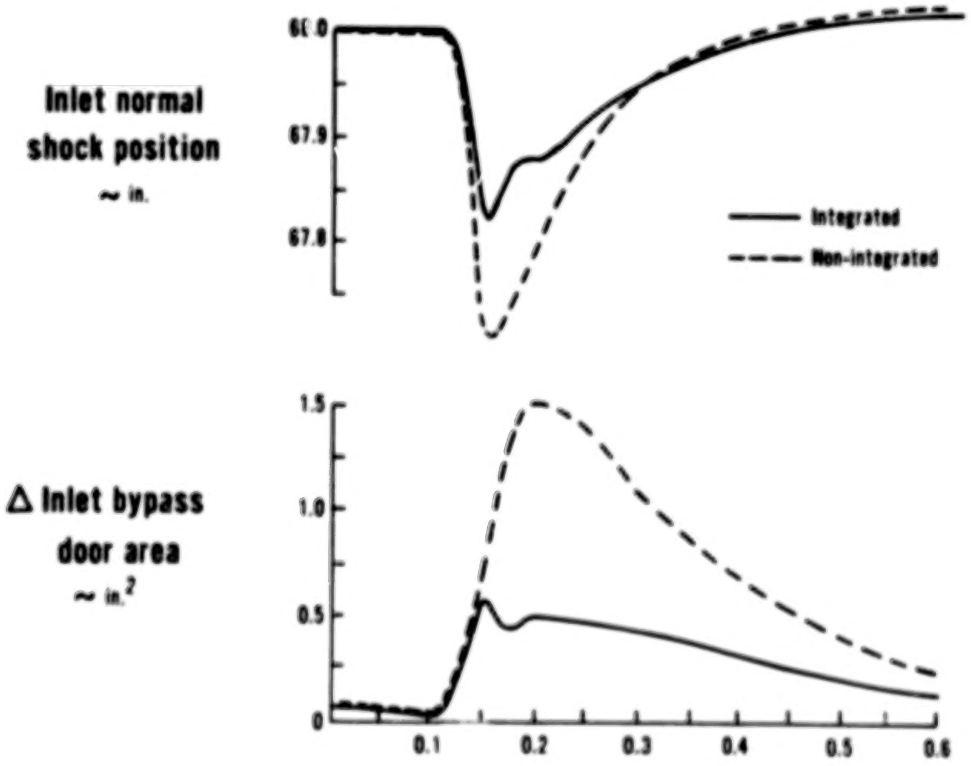


Figure 10 Transient Response to a Duct Burner Light-Off

CONCLUSIONS

The conceptual integrated control mode, for an Advanced Supersonic Transport propuision system, evaluated in this study, makes use of several cross-coupling paths between inlet and engine control variables and inlet and engine sensed variables. Design of the control loop gains and dynamic compensation for such a control mode can be effectively accomplished utilizing a multivariable control design technique based on Linear Quadratic Regulator Theory. Such integrated control modes may provide operational and performance benefits such as minimizing the use of inlet bypass doors for shock position control.

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PROPULSION CONTROLS

A LOOK INTO THE FUTURE

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SUMMARY

Increased system requirements and functional integration with the aircraft have placed an increased demand on control system capability and reliability. To provide these at an affordable cost and weight and because of the rapid advances in electronic technology, hydromechanical systems are being phased out in favor of digital electronic systems. The transition is expected to be orderly from electronic trimming of hydromechanical controls to full authority digital electronic control.

INTRODUCTION

Alvin Toffler in his book *Future Shock* said — "We're all aboard a train which is gathering speed, racing down a track on which there are an unknown number of switches leading to unknown destinations. Most of us are in the caboose looking backward."

This can be expecially true for the propulsion control where there are at least two outside influences, engineers, directing the train. These are the airframe and electronics industries. The airframe industry provides requirements. The electronic industry provides technology.

Future propulsion system controls will be highly reliable full authority digital electronic with selected component and circuit redundancy to provide the required safety and reliability. Redundancy may include a complete backup control of a different technology for single engine applications. The propulsion control will be required to communicate rapidly with the various flight and fire control avionics as part of an integrated control concept.

Development of the technology for advanced control systems will continue to evolve in the ongoing progression from hydromechanical controls to prime reliable digital electronic control systems for advanced aircraft in the late 1980's and 1990's. Part of this technology progression has already taken place with programs supported by government and industry. Two such programs have been the Full Authority Digital Electronic Control (FADEC) program and the Integrated Propulsion Control System (IPCS) program. The FADEC program engine tested advanced technology control hardware. The IPCS program has developed and tested an integrated inlet/engine/nozzle integration concept in the F-111 aircraft. A planned NASA program, Integrated Aircraft Control Technology, will develop a dedicated F-15 flight test vehicle for integrated aircraft/propulsion control research.

CURRENT TECHNOLOGY

An early step at Pratt & Whitney Aircraft was the use of a limited authority supervisory digital electronic control and a full function hydromechanical control unit for the F100 engine. This combination

allowed the realization of some of the benefits of digital electronic controls while maintaining the proven reliability of the hydromechanical control.

The F100 afterburning turbofan, illustrated in Figure No. 1, is representative of current high technology engines. The F100 is a low bypass ratio, twin-spool, axial flow, augmented turbofan engine. The control, basically hydromechanical with digital electronic trim, sets performance by controlling the inlet guide vanes, compressor variable stators, compressor bleeds, main burner fuel, augmentor fuel and exhaust nozzle area. As the engine/control system is reaching maturity, the electronic trim control reliability and responsibility is increasing dramatically. In fact, current digital electronic reliability exceeds that of the hydromechanical. This same kind of supervisory system is currently being developed for advanced JT9D and JT10D commercial engines. A full function hydromechanical unit is included in these control systems to provide the confidence necessary to introduce digital electronic controls into commercial service.

TECHNOLOGY EVOLUTION

Hydromechanical systems are being phased out in favor of the more capable electronic systems. An orderly transition is expected over the next ten years as illustrated in Figure No. 2. First generation electronics — Electronic Engine Control (EEC) — act as a trim on the F100 hydromechanical control. Second generation electronics — Digital Electronic Engine Control (DEEC) act as a full authority control, but utilize a hydromechanical backup control. Third generation electronics — Full Authority Digital Electronic Control (FADEC) — provide primary and backup control.

The major obstacle to universal acceptance of electronic systems is their relatively high failure rate while operating under severe environmental stress. Simple engines can be controlled by hydromechanical devices that have demonstrated much higher reliability than current electronic computation devices. However, as computational complexity increases, the reliability of hydromechanical devices decreases more rapidly than that of the electronic devices. The electronic control system is projected to be more reliable than hydromechanical systems for the engines of the 1980's.

Several research and development programs are being conducted to evaluate the reliability of full authority digital electronic systems when subjected to the environment of JT8D and JT9D engines. For mid-term transport applications, a dual channel approach is being evaluated to provide acceptable system failure accommodation. A single channel full authority Digital Electronic Engine Control (DEEC) in combination with a limited capability hydromechanical backup control is being developed for advanced F100 engines. A full authority digital electronic control was also tested for an integrated inlet/engine/nozzle system in F-111 aircraft under the Integrated Propulsion Control System (IPCS) program.

Further development of electronic control technology is being conducted under the Navy Full Authority Digital Electronic Control (FADEC) program. The Pratt & Whitney Aircraft FADEC design features two processors in one box, selected redundancy, parameter synthesis, and built-in-test to provide a high degree of fault tolerance. Advanced component technology used in the Pratt & Whitney Aircraft FADEC design is based upon projections for production of a control system in the mid-1980 time frame. For example, both central processors will be implemented with three very large scale integration (VLSI), silicon-on-sapphire (SOS) complementary metal-oxide semiconductor (CMOS) devices. This degree will represent a significant technology improvement over an existing 11 chip LSI CMOS processor design, and indicates the rapid trend toward greater packaging density, higher reliability, and improved computational capability.

Another program being conducted as part of NASA's Energy Efficient Engine (E^3) program is identifying control technology areas requiring development. Programs like FADEC and E^3 should continue because as automatic controls become more commonplace in the consumer market, industrial research will focus more on that need and less on the special needs of the aerospace industry.

Electronic control system reliability will be enhanced by electronic controls with internal fault detection, parameter synthesis, and switching logic that will transfer data and control functions for fail-operational performance. Electronic controls today are structured around a multi chip processor. The cost of this processor will continue to drop as more complex architecture and instructions are included on each chip. As illustrated in Figure No. 3, cost per calculation is decreasing at a 50% per year rate. A significant improvement in reliability will also follow with development of a single chip microprocessor and the associated reduction in external circuit connections.

As illustrated in Figure No. 4, a propulsion control system is not just an electronic box, but consists of many other varied components which are optimized as a system to meet the system goals. It is important to continue technology development for all components of the complete propulsion control system to make possible the optimization of performance, weight, cost, reliability, maintainability and other operating benefits. Important hardware considerations include the advanced output interfaces, advanced sensors, control system environment, integration, and electronic and component reliability.

Further research is required on advanced output interface devices which can be incorporated into actuation systems to provide interfaces that are more compatible with digital computers. An example of such an interface is the pulse-width modulated solenoid, developed for a fuel metering valve under the NASA Digital Output Interface (DOI) program. New sensing devices for propulsion system parameters should be developed that are compatible with digital controls and will reduce the input interface hardware requirements.

Optical communication has been proven feasible and cost effective for aircraft use by the ALOFT study and demonstration program. Presuming that immunity from electromagnetic interference is necessary, optical data links that are suitable for use in the engine environment must be developed. Figure No. 5 illustrates some potential advantages of optical communication. Also, alternate interface configurations such as multiplexing of feedback signals to the control unit and locating power switching elements away from the computer control unit need to be pursued.

Electronic component reliability is adversely affected by increasing temperatures. Therefore, it is necessary to provide cooling to the digital electronic control unit. For engine mounted control systems, this cooling may be provided by flowing fuel through passageways in the control unit. This approach may not be adequate at the elevated ambient and fuel temperatures encountered during supersonic flight. Therefore, research into alternate cooling approaches should be conducted.

System integration of the propulsion and airframe would benefit from cooperative programs in which airframe and engine manufacturers consider: (1) supplying data from the aircraft central air data computer to the propulsion system controls; (2) supplying electrical and hydraulic power with acceptable characteristics from the aircraft power systems to the propulsion system controls; (3) configuring the control system and intersystem communication links to accommodate such problems as lightning strikes, EMI, and common mode failures; and (4) design of the control system to minimize damage resulting from engine fires.

A single channel digital control with selective component and circuit redundancy will result in a system of minimum cost and complexity, but requires considerable substantiation to ensure that acceptable reliability levels will be obtained without the use of redundant channels or backup control configurations. Technology advances are therefore required in the area of digital electronic components to provide continuing improvement in system reliability. Design studies are also required to determine how to utilize advanced technology components and features such as selective redundancy and fault tolerance logic to optimize the control system reliability. An Air Force sponsored program, "Digital Electronic Control System Reliability," has a goal to establish the definition of a Full Authority Fault-Tolerent Electronic Engine Control (FAFTEEC) system that has significantly better reliability than any of the electronic or hydromechanical alternatives and still maintains performance, cost and weight advantages. Figure No. 6

illustrates the goals of this program. Selected redundancy will be utilized to minimize mission cost/effectiveness.

Software development areas include propulsion and flight controls integration and the application of advanced control methods. Because of the flexibility and logic programming capability of full authority digital electronic controls, a number of sophisticated control functions can be incorporated which will promote efficient propulsion system operation, reduce pilot workload, improve safety of operation, potentially reduce fuel consumption, and make the control system less sophisticated for the user. For advanced supersonic transport and fighter aircraft applications, further technology development is required in the area of integrated aircraft/inlet/engine/nozzle control modes. Control algorithms should be investigated to improve the logic capability of the digital control instead of implementing hydromechanical control logic in electronic boxes. Technology development would also be desirable for performance seeking controls and integration with Engine Condition Monitoring functions. Performance seeking logic can be implemented on-line to provide improvements in propulsion system and aircraft system performance through optimization of control variable settings. The software capability of the propulsion control can be used to provide data to an engine condition monitor which analyzes the mechanical health and component efficiency of the engine to provide early identification and prevention of problems, thereby reducing operating and maintenance costs.

Closed loop test benches like the one illustrated in Figure No. 7 will be utilized to verify hardware and software concepts even before engine definition. As illustrated, a hybrid computer can simulate the aircraft and the engine components that "turn and burn" — compressors, burners, turbines, augmentors, etc. Control components are driven such that "real" engine operation is simulated.

INTEGRATION

The design of propulsion systems has traditionally been based on the primary objective of maximizing steady-state performance of the total vehicle. New aircraft designs and technology advancements are giving designers a great range of aerodynamic and propulsive capabilities for interactive/integrated force controls. This requires that the configuration be visualized in terms of concepts such as force production, force distribution and force management. Force production incorporates aerodynamic propulsive interactive force systems such as in-flight vectored thrust, in-flight reversed thrust, jet flaps and external blown flaps. Force distribution includes advanced concepts such as relaxed static stability, canards and maneuver flaps. Force management includes features such as flight propulsion control, coupling systems, maneuver load control, direct lift control, direct side force control, energy management and energy maneuverability.

Figure No. 8 illustrates a few potential next generation aircraft. These aircraft will dynamically blend the control functions of the weapon system. An example would couple flight control, propulsion control and laser tracker control to the weapon fire control with the object being to maximize aiming precision or target range. Performance seeking control actions could be supervised by the mission control system. Algorithms could be selected to maximize range, minimize time-to-target or maximize flight time. Contributing systems (flight, propulsion, navigation) could optimize performance while simultaneously observing subsystem limits. Research to define these blended control modes will require cooperative "team" studies to assure that each subsystem is properly represented and modeled with adequate fidelity.

CLOSING THOUGHT

The technologies supporting control system evolution draw from a wide variety of disciplines. While some of these disciplines are paced by progress within the aerospace community, most of them are now heavily influenced by the demands of the consumer industries.

As automatic controls become more commonplace in the consumer market, industrial research will focus more on that need and will respond less to the special needs of aerospace products. Although some consumer products and techniques will be adaptable to our needs, the net effect will be a requirement to expend more research dollars for aerospace specialty items.

Research money alone will not, however, reverse the current trend of specialty industries to ignore or reject the aerospace market. Within these industries we see a rare consensus between the "managers" and the "innovators" that aerospace products are not worth the trouble. In addition to a low profit margin, the managers see a poor return on the investment of time and limited innovative talent. This reinforces their natural desire to constrain the innovations and react only to the consumer market. The innovators are not stimulated because long range military missions, plans and products are not visible to them. In addition, their novel or revolutionary ideas are frequently "stonewalled" by Military Specifications.

There are many other factors involved in this problem and a solution is not obvious. Some research effort should be expended to define new planning, budgeting and procurement procedures plus new technology management methods that will encourage these specialty item subcontractors to participate in aerospace product development.

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F100 TURBOFAN WITH AUGMENTOR

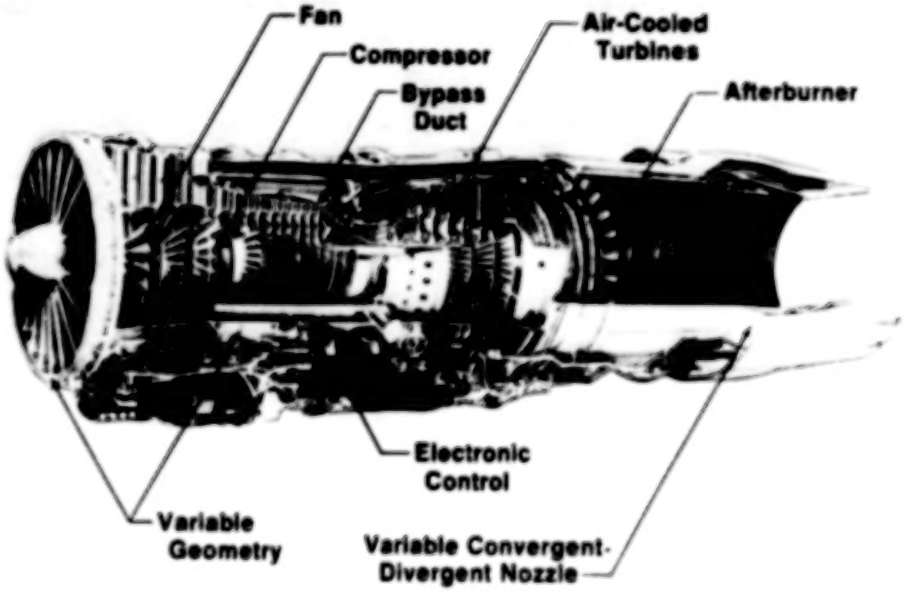


Figure No. 1

ORDERLY TRANSITION TO ELECTRONIC CONTROL

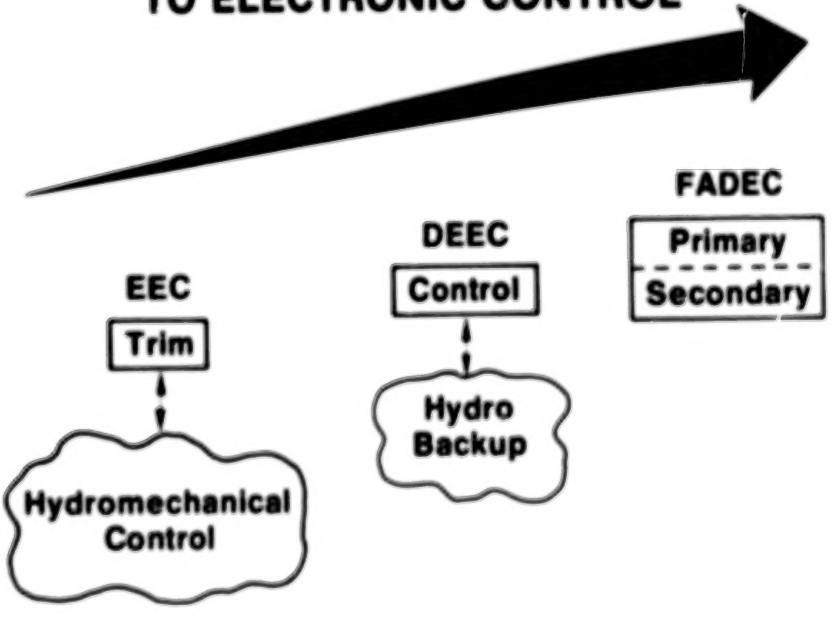


Figure No. 2

ELECTRONIC COST PER CALCULATION REDUCING 50% PER YEAR

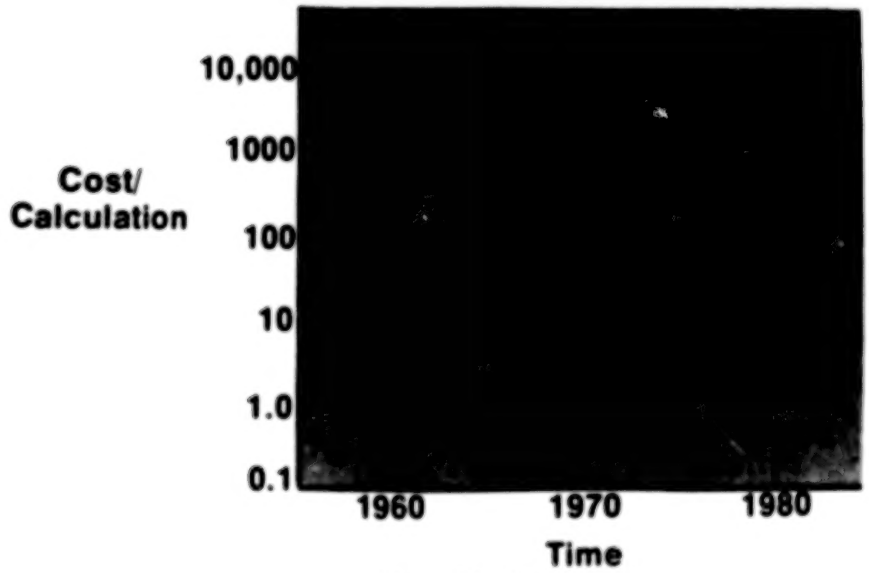


Figure No. 3

CONTROL TECHNOLOGY/GOALS

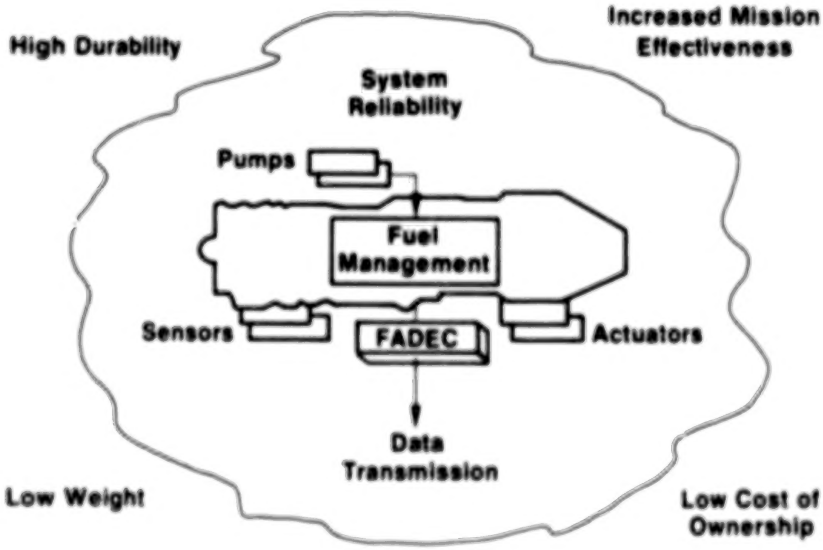


Figure No. 4

FLY BY LIGHT

Engine Cable Weight Reduced
High Data Rate
No Electromagnetic Interference



Fail Gracefully
Security - No Leakage
Direct Communication With Computer

Figure No. 5

RELIABILITY WITH REALISM

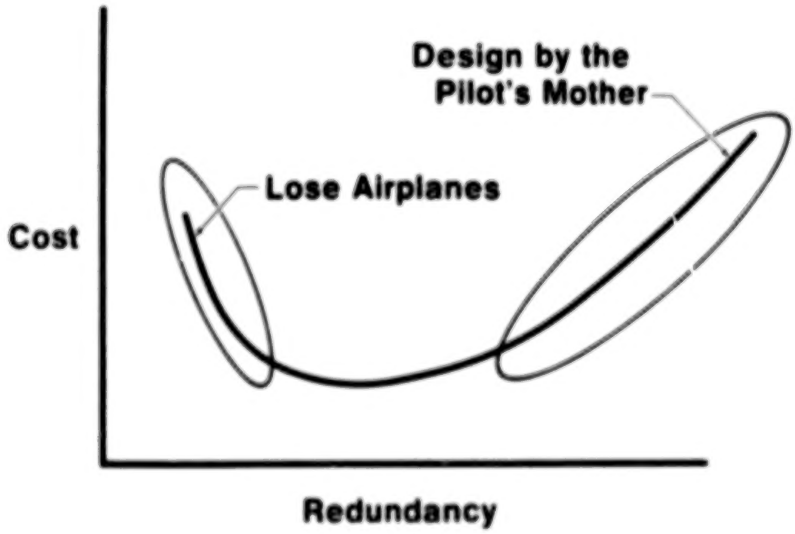


Figure No. 6

CONTROL SYSTEM DEVELOPMENT/ INTEGRATION FACILITY

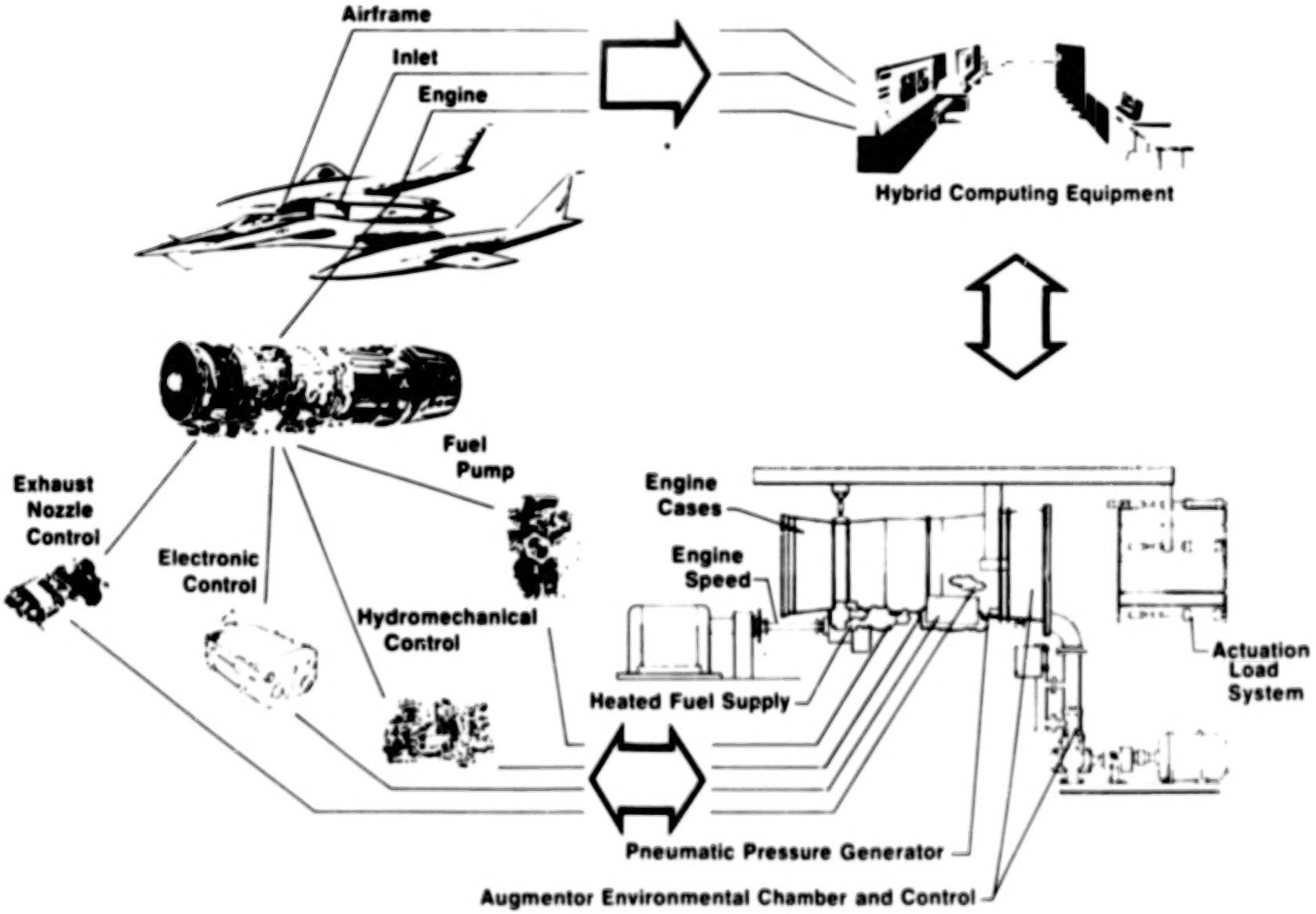


Figure No. 7



Figure No. 8

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DIGITAL ELECTRONIC ENGINE CONTROL FOR FUTURE FIGHTER AIRCRAFT

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McDonnell Aircraft Company

ABSTRACT

The evolution of MCAIR's experience in aircraft flight control systems was reviewed. The development illustrates the transition from the F-4 mechanical flight control system with analog stability augmentation to the F-18 digital electronic fly-by-wire system. The resulting technology from this evolution is directly applicable to digital electronic control for advanced fighter engines. Digital electronic control provides potential benefits for the propulsion system, which includes the inlet, engine, and nozzle. It also facilitates control of variable-cycle engines and the integration of the propulsion system with other aircraft systems. The fundamentals which impact installed performance and response of the propulsion system provide baseline requirements for further improvement due to electronic control. Other desired benefits include improved handling, performance, and stealth as well as reduced operations and support costs. MCAIR envisions flight-propulsion control coupling in all advanced fighters. Study of a typical air superiority fighter illustrates the effect that potential propulsion system improvements have on takeoff gross weight and life cycle costs. Payoffs are also identified from current AFFDL and NASA studies on integrated control. These include closed-loop speed control using a thrust reverser and energy management for intercept. Furthermore in-house V/STOL studies illustrate the significance of integration in this application. Finally, a typical airframe and engine development schedule indicates the technical and managerial challenges of integrated control concepts. The summary includes a definiton of typical control system development events and the technical needs for integration of the aircraft and propulsion systems.

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FUTURE AIR FORCE AIRCRAFT PROPULSION CONTROL SYSTEMS -

THE EXTENDED SUMMARY PAPER

Charles A. Skira
Air Force Aero Propulsion Laboratory

Future military aircraft propulsion control systems will be full-authority, digital-electronic, microprocessor-base systems. By now, this should not surprise anyone, in fact, for someone who has been close to propulsion control development, this statement is widely accepted. I feel silly just writing it. If you were looking for a real grabber of an opening paragraph, I'm sorry.

The evidence in support of such a bold prediction is overwhelming. Currently and for the near-term future, propulsion system performance increases will be made through the exploitation of advanced variable geometry components. As shown in Figure 1, unless there is a breakthrough in component technology, performance increases will result in additional engine complexity. In other words, the control system will have to control more variables, more closely and faster than ever before. Hydromechanical control technology simply cannot compete against the performance benefits offered by electronics.

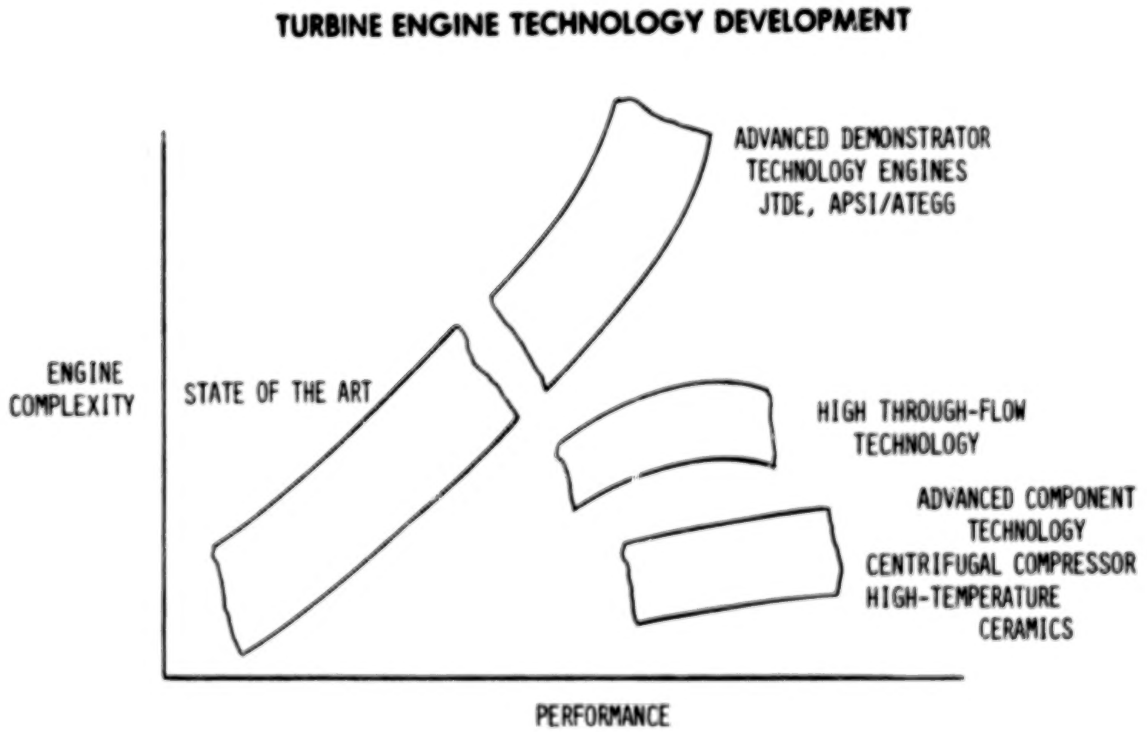


Figure 1

Now that the future has been defined, what should the Air Force's role be in the development of these systems? Clearly, we cannot expect to begin to develop new and better microprocessors and associated hardware. It is difficult just to keep up with the advances in computer technology. However, we can begin to plan for the day when microprocessor technology will permit the integrated control and management of the aircraft flight control, fire control and propulsion control systems and throw in maintenance and diagnostic information for free.

Therefore, in the Air Force Aero Propulsion Laboratory, we have concentrated on the development of control logic algorithms with every expectation that they will be put into workable software ultimately. We are confident that digital electronic controls systems will begin to really payoff when the full capability and power of the microprocessor is utilized. At the rate that microprocessor capability is expanding, we may never be able to use it all. However, our ultimate goal in the area of logic development is to be able to accomplish real-time, adaptive control of the aircraft propulsion system. For a propulsion system, this is a challenging problem for sure. The present pathway toward achieving this goal is the subject of the rest of this paper.

FUTURE PROPULSION CONTROL

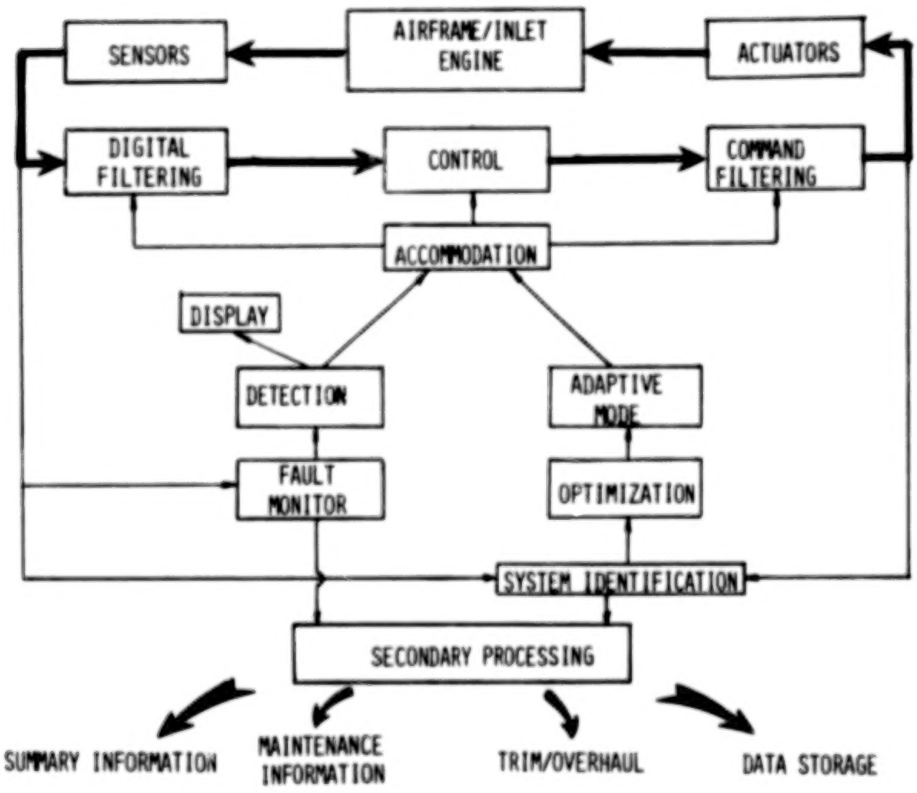


Figure 2

A schematic of the propulsion system control and information management system is shown in Figure 2. Single, closed-loop control of the engine is shown in dark lines. The dark lines indicate which part of the control and information management function can be done real time with current state-of-the-art hardware and software technology. In our current activities, we are developing basic control logic algorithms based on linear quadratic synthesis techniques and various schemes based on filter theory for sensor failure detection and accommodation and to a limited extent actuator failure detection and accommodation. At this point in time, actuator failure accommodation consists of a reversion to an independent back-up control system. Just how to accommodate an actuator failure without seriously degrading engine performance by way of reconfiguring the control law to account for the loss of controllability is an attractive and needed research area.

Our current planned research activities include an increasing emphasis on the development of real-time system identification techniques. It is obvious to us that this is an extremely important and vital area that will enable us to develop a real-time adaptive control. Research in this area has been ongoing with the initial emphasis on identification of aircraft handling qualities. Research in developing real-time identification methods has begun.

With the knowledge of the engine's current operating characteristics, adaptive control techniques can be implemented. Such a scheme would involve on-line optimization based on continuous observations of engine operating parameters. Adjustments to the control logic would then be made.

System identification methods may also be used for engine diagnostics. The technique would isolate a faulty engine component or sensor based on comparisons of observed engine behavior with nominal engine behavior. The results of such an analysis could be used to trim up or adjust for the loss in performance by way of an adjustment to the control logic. A sensor failure, for example, would result in the reconstruction of that measurement in the signal conditioning logic so it would continue to operate without any perceivable change in performance. In any event, the results would be saved and used later for maintenance purposes.

As shown in the figure, the development of a control and diagnostics capability is a logical evolution of such an approach. Unfortunately, the prevailing opinion of Government and industry is that the integration of control and diagnostics is revolutionary, not evolutionary. In an industry where change is both painful and slow, it would appear easier to reduce the national debt. Despite the internal and political resistance, which is great, technical advancements and a carefully orchistrated effort on the part of the Government agencies who sponsor research in this area may just pull it off.

Such a system, when implemented, would involve several microprocessors working together in parallel being monitored by a master control or supervisory computer. Such a concept of a distributed, microprocessor-based control system is shown in Figure 3. What looks like a system designer's nightmare will have to be another area of intense research activity. The microprocessor is breaking down the conventional divisions between software and hardware —

LARGE-SCALE CONTROL

DISTRIBUTED SYSTEMS

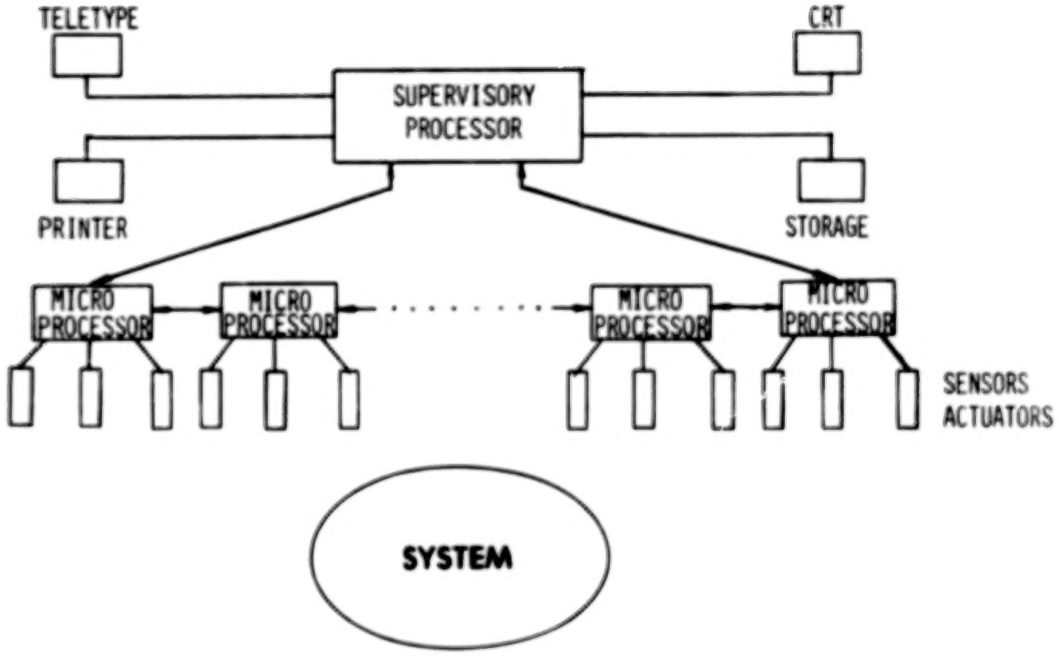


Figure 3

the new definition is firmware. Control design engineers will by necessity become electronics engineers.

Fortunately, aircraft propulsion systems will not lead the way, already energy-minded industries involved in process control are utilizing microprocessors to optimize system efficiency and save energy costs. However, the engine control problem is unique and will require more foresight, greater imagination and more coordination on the part of Government and industry alike. Greater emphasis will be placed on concept demonstration and validation. A large ongoing commitment in terms of facilities and test beds within the Government is vital to the successful implementation of the concepts presented in this paper.

In conclusion, we in the Air Force have defined the problem and proposed an outline of an approach to accomplishing a real-time, adaptive control and diagnostic information system. Such a task requires further research in several areas. These are listed below in Table I. Some areas have been the focal point of generic development activity and the investigation of how these techniques may be applied to the propulsion control problem remains to be investigated. In some areas, such as linear quadratic synthesis and multi-

variable frequency methods for control logic development, applications to the propulsion control problem have been investigated. In other areas, basic research is needed. In any event, a coordinated research effort on the part of the Air Force, NASA, and the Navy is needed.

TABLE I. - AREAS OF FUTURE RESEARCH

- Systems Modeling
- System Identification
- Multivariable Control
  - Frequency Domain
  - Time Domain
  - Discrete-Time Control
- Stochastic Control
- Distributed Systems
- Hierarchical Control
- System Reliability/Integrity
- Filtering/Estimation
- Failure Accommodation
  - Fault Detection
  - Fault Isolation
- Adaptive Control/Optimization
  - Performance Seeking
  - Real-Time Optimization

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IMPLICATIONS OF DIGITAL CONTROL ON ENGINE CONTROL STRATEGIES

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ABSTRACT

With the advent of on-board digital hardware the constraints imposed by the current hydromechanical and analog engine controls no longer apply. In this talk, the capabilities and opportunities of digital engine controls were discussed. As an example of the current state of the art of advanced digital controls, the capability of the Navy Full-Authority Digital Electronic Control (FADEC) was reviewed. This control includes a closed-loop multivariable design as well as failure detection and correction strategies for sensors and actuators. Thus one can conclude that there is capability to apply much of the existing control theory to provide better and more reliable engine control. However, through examples, it was shown that existing techniques provide only a small part of necessary control logic. The problem is that the engine is nonlinear, with parameters that depend on operating conditions. Currently these nonlinearities are handled in an ad-hoc manner. Thus, there is a need for a more systematic nonlinear control design approach. A couple of possible approaches were suggested.

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SHOULD WE ATTEMPT GLOBAL (INLET-ENGINE-AIRFRAME) CONTROL DESIGN?

Christopher M. Carlin
Boeing Military Airplane Company
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SUMMARY

The Lewis-APL MultiVariable Control (MVC) program has demonstrated that MVC design techniques are applicable to engine control algorithm design. MVC has also been applied to other aircraft systems, flight control and functions, and energy management. The next major step is to consider the global problem - multivariable design of the entire airplane control system. An intermediate step in that direction is to design a control for an inlet-engine-augmentor system by using MVC techniques. Two valuable opportunities to do this and to exercise the results experimentally are available in the near future.

The Supersonic Cruise Research (SCR) large-scale-inlet research program will provide an interesting opportunity to develop, integrate, and wind tunnel test a control for a mixed-compression inlet and variable-cycle engine (VCE). The Integrated Propulsion Airframe Control (IPAC) program will introduce the problem of implementing MVC within a distributed processing avionics architecture, requiring real-time decomposition of the global design into independent modules in response to hardware-communication failures. As IPAC progresses beyond multivariable design of the propulsion system, it will provide a real-world environment in which to address more basic questions: Should we attempt global control design? Is it practical or desirable? What is the required methodology?

DISCUSSION

The Lewis-APL MVC program, figure 1, demonstrated that for an advanced engine, P&WA F100, multivariable control techniques can be used vigorously to design an engine control system. The quality of the resulting system was demonstrated by its test in the altitude cell at Lewis. Program documentation provides a basis for undertaking more complex multivariable design tools.

Current airplane control systems are designed, figure 2, with a minimum of interaction and integration, partially because of a historical lack of communications ability and partially because of a concern over failure propagation through integrated subsystems. Lack of integration penalizes the design of airplanes with strong aerodynamic-propulsion coupling - SST and V/STOL, for example. New technology and research programs, figure 3, provide the opportunity to design a highly integrated airplane control system. Ideally, this new "global" system will have fewer actuation and sensor components and superior performance and fault tolerance.

Substantial effort is required to reduce the global design concept to practice. Because the design process is configuration dependent, a specific airplane must be addressed. To ensure that the design and the testing of the design truly demonstrate reduction to practice, the selected airplane or propulsion system should be realizable and eventually be tested in the wind tunnel or preferably in flight. Two planned NASA programs, IPAC and the SCR inlet control program, provide appropriate opportunities to address the real-world problems, figure 4, of global design.

The NASA Lewis SCR inlet control program encompasses the design, development, and testing of a supersonic propulsion system that incorporates a mixed-compression inlet and a variable-cycle engine. The system interactions among the components and with the environment, figure 5, are complex; the typical propulsion control system will have six or more actuated variables and 10 or more sensed variables. Thus, the system represents an appropriate example on which to exercise multivariable control technology. The program schedule, figure 6, currently calls for a relatively long design and development cycle leading to closed-loop wind tunnel testing in 1983 and a flight inlet design in 1985.

The NASA DFRC IPAC program, figure 7, is intended to demonstrate the methodology and benefit of integrated flight and propulsion controls on a high-performance aircraft having variable-geometry external compression inlets. It is a multifaceted program that provides the opportunity to test multivariable control algorithms, advanced engine control hardware (FADEC), and data bus integration of avionics and control systems.

The elements of the IPAC system, figure 8, communicate via a MIL 1553 data bus that provides orders of magnitude greater communication potential than ever before available. Control system software will be structured to permit rapid system adaption in order to take advantage of control system concepts identified during flight testing and to implement new research tasks as they are identified.

Multivariable control technology has been applied to many aspects of the flight control problem, usually as one design tool among many, figure 9. Typically, the engine response has been highly simplified or neglected completely. This approach is acceptable for a conventional airplane, figure 10, in which each control affects one principal axis and coupling is deliberately minimized. In advanced aircraft, figure 11, frequently this is not economically practical and the active control system must provide the solution. In both research and practice limited solutions have been provided. Each starts from an existing limited base and fails to incorporate all the available technologies into a top-down design methodology. The IPCS program, figure 12, demonstrated full-authority digital propulsion system control but only demonstrated in a very limited way the potential for direct electronic integration of the autopilot and engine control. The conjunction of multivariable control algorithm development with the realities of hardware implementation, figure 13, must also be considered if a successful fault-tolerant design is to be created. The typical advanced control will probably have only 30 percent of its functions directly associated with control. The remainder will be related to communication, fault tolerance, maintenance (BIT), and propulsion system condition monitoring.

If the benefits of multivariable control research are to be achieved and demonstrated, an integrated cohesive research program, figure 14, supported by NASA and the DOD agencies is an absolute must. The problem of global design cannot be successfully approached on a piecemeal basis.

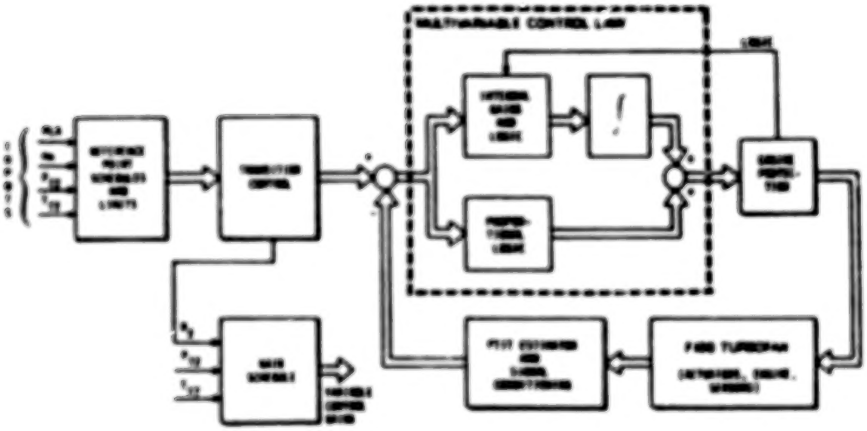
The problems associated with global control design, figure 15, are both technical and managerial. The technical areas are generally resolvable if sufficient time and effort are applied. The major managerial problem is that the real reward of integration does not lie in simple performance inprovement, another 5000 feet of altitude, for example. It lies in reliability, maintainability, pilot workload and skill level, and other things which are relatively intangible. Thus a control engineer concerned with inproving the product frequently finds it difficult to obtain the necessary resources. Organizational barriers also present a real but solvable problem to global control system design.

A major payoff from multivariable control design is the elegance of the resulting design, figure 16. The structure is clear and, to a degree, common from design to design. Component requirements are clearly developed as part of the design process, and standardized architectural elements should lead to standard hardware and software modules, thus reducing design cost and enhancing reliability.

CONCLUSIONS

The groundwork, figure 17, for global control design is provided by a prior research program. The need for it exists through the efforts of advanced airframe and engine cycle designers. A research program is required to carry out the design of the global control for a complex engine-airplane system and to flight test the resulting system in order to clearly demonstrate the utility of the existing technologies in addressing the problem of integrated control system design.

F100 MULTIVARIABLE CONTROL



- ENGINE ONLY
- TESTED IN ALTITUDE CELL
- WELL DOCUMENTED
- CLEARLY DEMONSTRATES UTILITY OF MVC

Figure 1

CURRENT AIRPLANE
CONTROL SYSTEM DESIGN

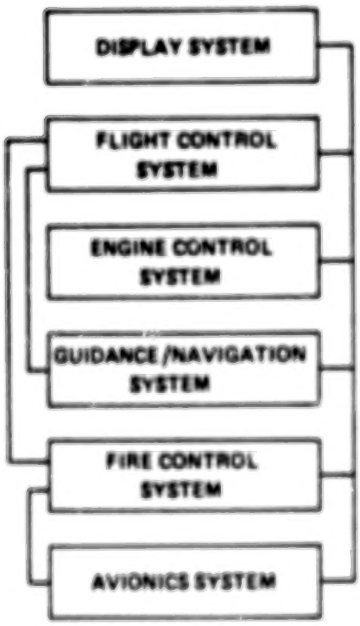


Figure 2

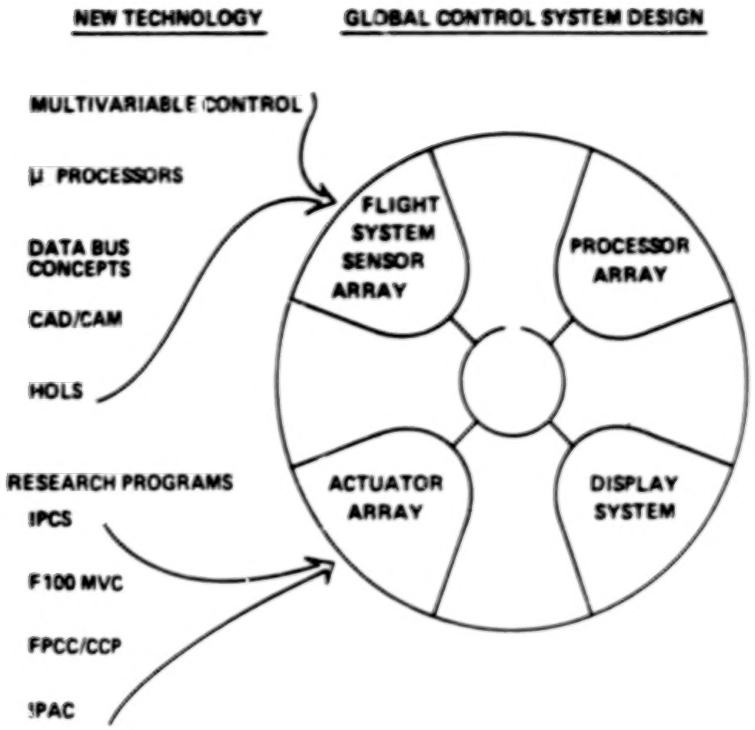


Figure 3

MVC EXTENSION TO PROPULSION SYSTEMS

- CANDIDATE SYSTEM REQUIREMENTS
  - REAL
  - SIGNIFICANT INLET/ENGINE/AUGMENTOR INTERACTION
  - FULL SCALE TEST PROGRAM PLANNED
- POSSIBLE SYSTEMS
  - INTEGRATED PROPULSION AIRFRAME CONTROL (IPAC)
  - SUPERSONIC CRUISE RESEARCH (SCR) INLET CONTROL PROGRAM
- ADDRESS REAL WORLD PROBLEMS
  - SENSOR LOCATION
  - AVIONICS ARCHITECTURE
  - RELIABILITY
  - REDUNDANCY
  - FAULT TOLERANCE
  - DISTRIBUTED SYSTEMS
  - AIRFRAME INTERACTION

Figure 4

VSCE PROPULSION SYSTEM INTERACTIONS

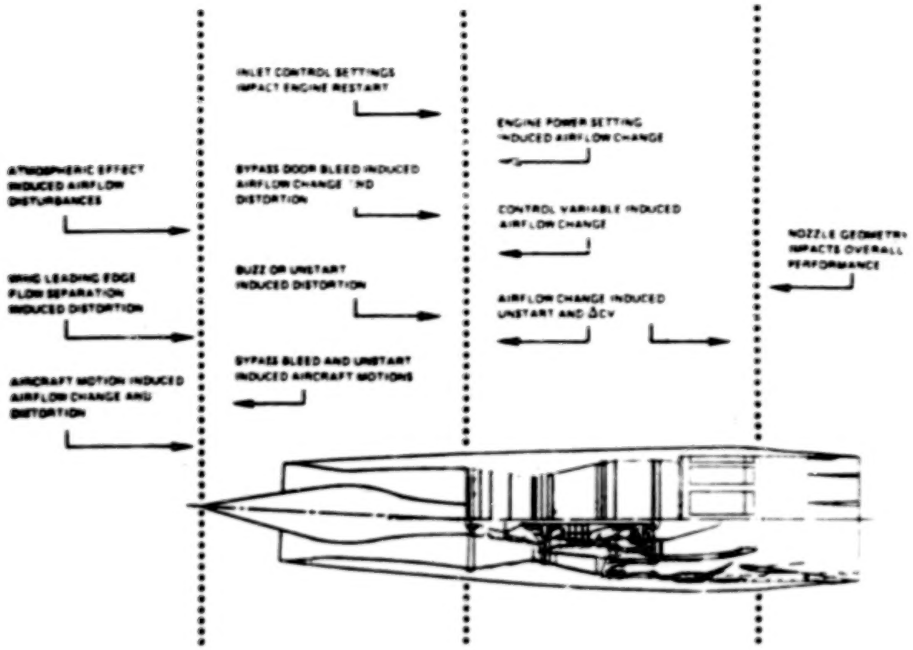


Figure 5

SCR SUPERSONIC PROPULSION SYSTEM CONTROLS RESEARCH

- SYSTEM
  - MIXED COMPRESSION INLET
  - VARIABLE CYCLE ENGINE
  - AIRFRAME AERODYNAMIC COUPLING
- SST CONTROLS CHARACTERISTICS
  - HIGH BAND PASS INLET ACTUATION
  - AD HOC FCS PROPULSION INTERFACE
- MODERN CONTROL PAYOFF
  - REDUCED ACTUATION REQUIREMENTS
  - IMPROVED SENSOR SELECTION
  - ACHIEVE REDUNDANCY THROUGH MULTIVARIABLE ANALYSIS OF AERO COUPLING

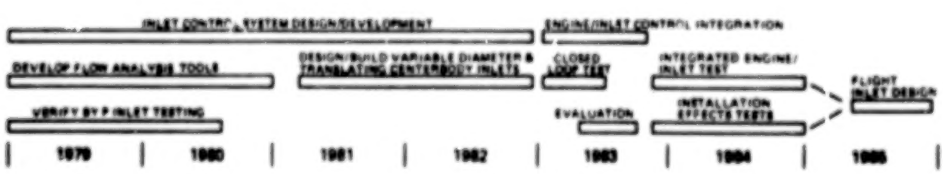


Figure 6

INTEGRATED PROPULSION - AIRFRAME CONTROL (IPAC)

PROGRAM PARTICIPANTS

- NASA DFRC
- NASA LERC
- USAF APL
- USAF FPL
- NAVY NAPC

DEVELOP A FLEXIBLE RESEARCH FACILITY WITH INTEGRATED ENGINE - INLET AND FLIGHT CONTROLS

- DEVELOP CONTROL LAWS TO
  - REDUCE FUEL CONSUMPTION
  - IMPROVE PERFORMANCE
  - INCREASE MANEUVERABILITY
  - REDUCE LIFE CYCLE COSTS
- PROVIDE CONTROL TECHNOLOGY FOR FUTURE

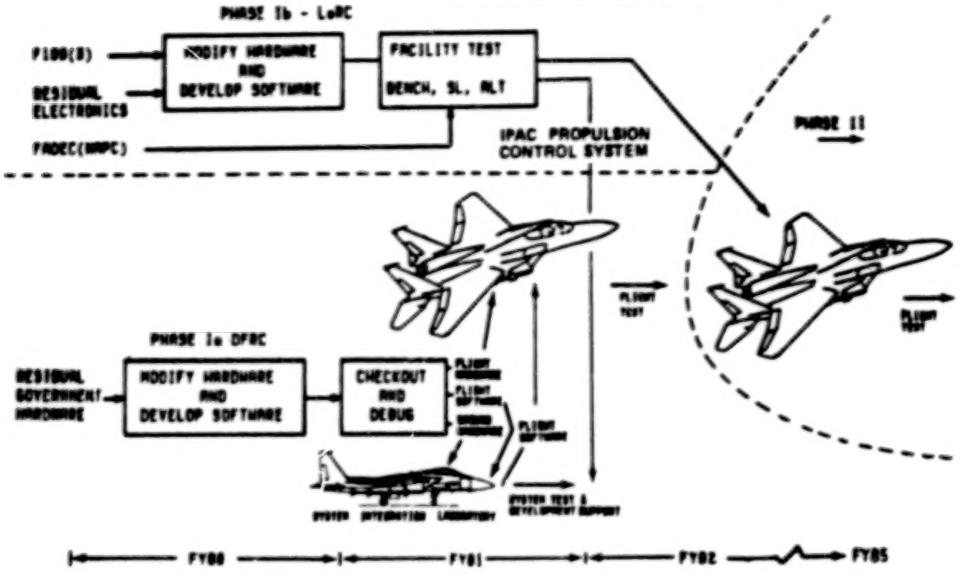
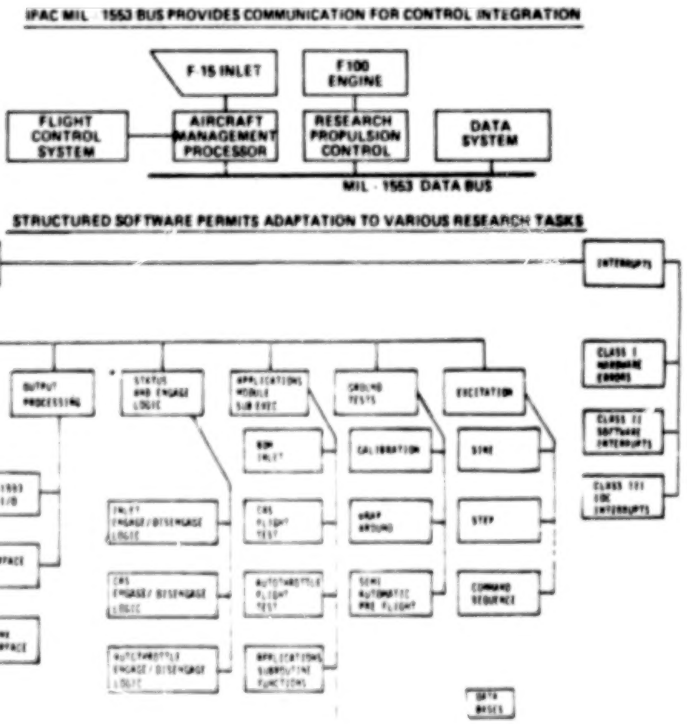


Figure 7



CONTROL - CONFIGURED VEHICLE RESEARCH

Figure 8

MULTIVARIABLE CONTROL TECHNOLOGY IS WIDELY APPLIED IN FLIGHT CONTROLS

- OVERALL DESIGN TOOL
  - SYSTEM IDENTIFICATION
  - STATE REDUCTION
  - CONTROL DECOUPLING
  - SENSOR SELECTION
  - MODE OPTIMIZATION
  - SAMPLING EFFECTS
    - DIRECT DIGITAL
    - CONTINUOUS TRANSLATED
- APPLICATIONS
  - F-8C NASA (LRC/DFRC) DFBW
  - DAST II
  - L-1011
  - 757
  - 767
  - B-1, B-52 OPTIMAL TERRAIN FOLLOWING

ALL APPLICATIONS HAVE MINIMUM TREATMENT OF PROPULSION SYSTEM

- PILOT SELECTED THRUST
- THRUST IS A SIMPLE LAG ON PLA

Figure 9

CONTROL-CONFIGURED VEHICLE RESEARCH

- CONVENTIONAL APPROACH - DECOUPLED DESIGN



PITCH ROLL THRUST

- CONTROL-CONFIGURED VEHICLE RESEARCH
  - IMPROVED HANDLING QUALITIES (NUMEROUS)
  - FLIGHT ENVELOPE LIMITING (F-101, F-103)
  - REDUCED STATIC STABILITY (C-5A, F-4, YF-16)
  - GUST ACCELERATION REDUCTION (B-52, XB-70, B-1, C-5A, YF-12)
  - MANEUVER LOAD CONTROL (MLC)
    - FIGHTER TYPE – MINIMUM DRAG DURING MANEUVERS (F-4, YF-16)
    - TRANSPORT TYPE – MINIMUM STRUCTURAL FATIGUE (B-52, C-5A)
  - ACTIVE CONTROL OF STRUCTURAL MODES (B-52, YF-12)
  - PROPULSION/DIRECTIONAL CONTROL MODES (YF-12)
  - AUTOMATIC TERRAIN FOLLOWING (B-1, B-52, F-111)
  - ADVANCED FIGHTER TECHNOLOGY INTEGRATION (AFTI) (F-111)

Figure 10

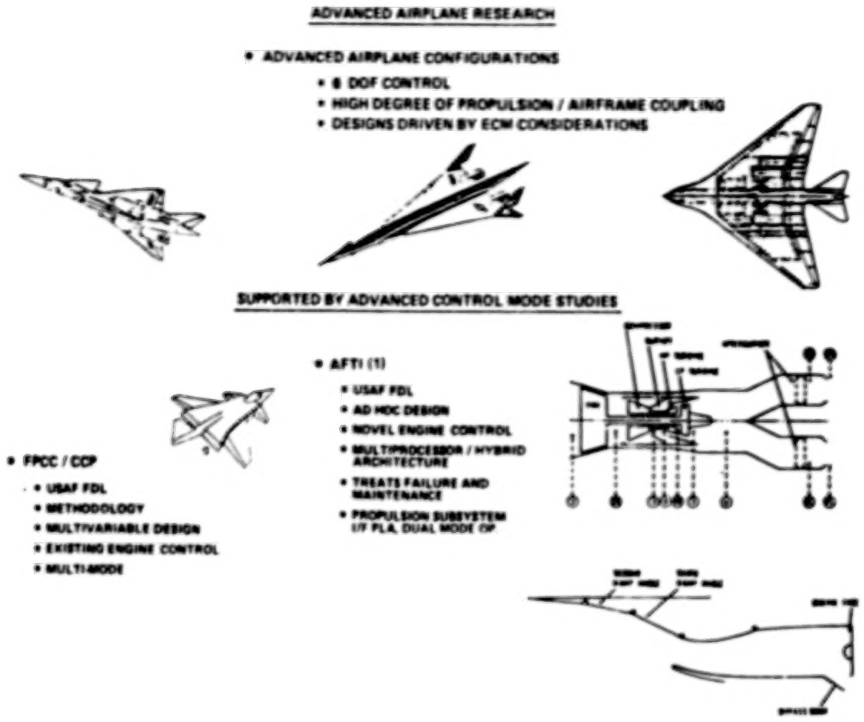


Figure 11

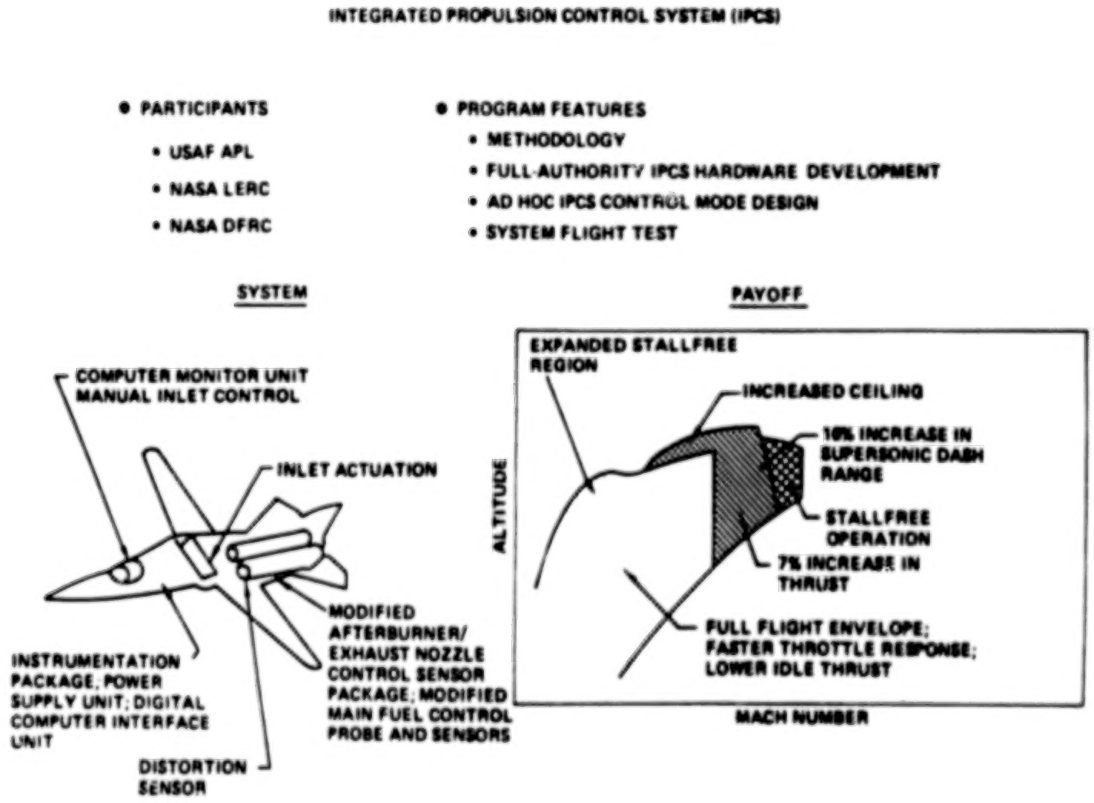


Figure 12

- MULTIVARIABLE CONTROL THEORY INTERACTS WITH SYSTEM ARCHITECTURE AND EQUIPMENT CHARACTERISTICS

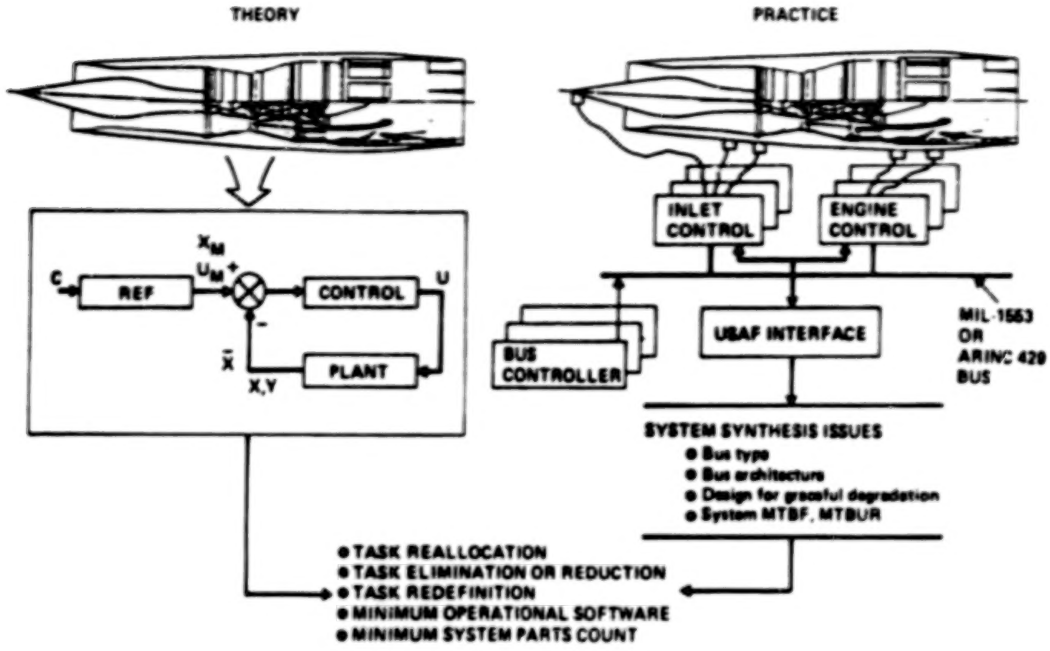


Figure 13

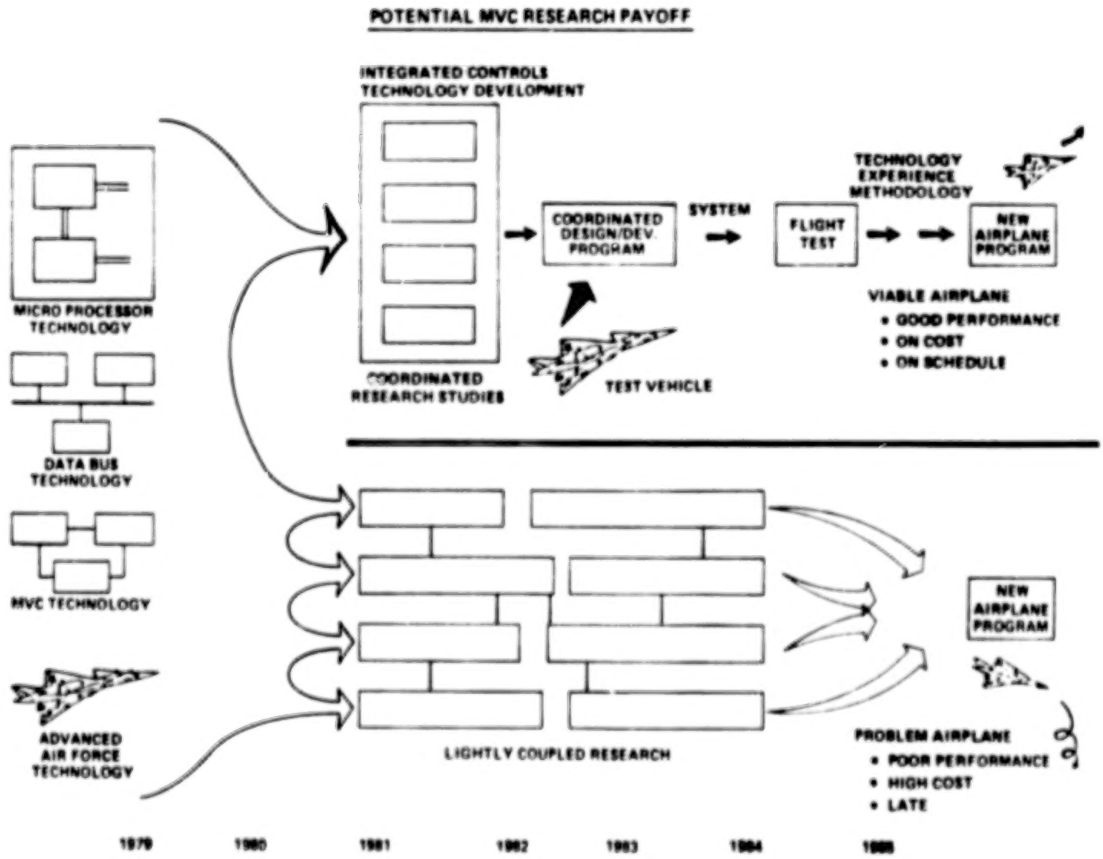
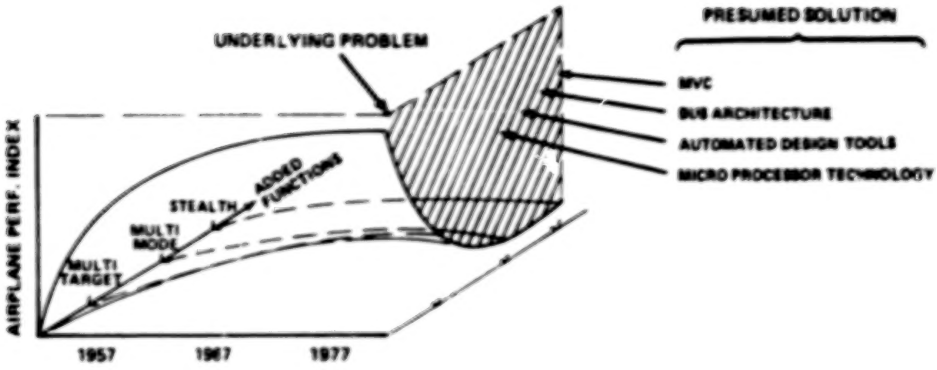


Figure 14

PROBLEMS OF GLOBAL APPROACH TO MVC



IMPLEMENTATION PROBLEMS

TECHNICAL

- SIZE OF PROBLEM
- INTERFACE TO STRUCTURED PROGRAM
- AUTOMATED DESIGN EXECUTION
- GRACEFUL DEGRADATION IN AUTOMATED SYSTEM
- SUBSYSTEM I/F ARE NO LONGER SIMPLE
- SOLUTIONS AND PAYOFFS ARE SENSITIVE TO PLANT

MANAGEMENT

- CROSSING STAFF LINES
- CROSSING CORPORATE LINES
- DEFINING ORGANIZATIONAL RESPONSIBILITIES

Figure 15

MULTIVARIABLE CONTROL SHOULD LEAD TO ELEGANT DESIGN

• STRUCTURE		
• STRUCTURED IDENTIFIABLE ARCHITECTURE	VERSUS	RANDOM LOGIC
• COMPUTATION REQUIREMENTS		
• IDENTIFIABLE ITERATION RATE REQUIREMENTS	VERSUS	EMPIRICAL SELECTION
• IDENTIFIABLE PRECISION REQUIREMENTS	VERSUS	EMPIRICAL SELECTION
• HARDWARE		
• STANDARD CONTROL PROCESSOR AND LANGUAGE	VERSUS	DIVERSE TYPES

Figure 16

CONCLUSIONS

- RESEARCH PROGRAMS HAVE PROVIDED GOOD GROUNDWORK FOR GLOBAL CONTROL DEVELOPMENT
- AIRPLANE DESIGNERS / ENGINE CYCLE DESIGNERS ARE IMPOSING A HIGHER LEVEL OF INTEGRATION
- A PROGRAM(S) IS REQUIRED TO –
  - SHOW BENEFITS / COSTS
  - EXERCISE AUTOMATED DESIGN PROCESSES
  - VERIFY TECHNOLOGY READINESS
- DEMONSTRATION OF READINESS REQUIRES REALISTIC ENVIRONMENT –
  - ARCHITECTURE
  - INTERFACES
  - RELIABILITY
  - REDUNDANCY

Figure 17

ROAD MAP TO ADAPTIVE OPTIMAL CONTROL

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Indianapolis, Indiana

Early application of full-authority digital controls to existing jet engines involved duplication of the existing hydromechanical control logic in digital form, and this provided little improvement in performance. Presently there are several different programs to apply digital controls to advanced variable-cycle engines (VCE's). DDA has already run the GMA 200 gas generator and the GMA 200 Joint Technology Demonstrator Engine (JTDE) under various levels of digital control employing digital logic designed specifically for digital control of these engines. In each case, the control was "optimized" according to a digital model of the engine, and the actual optimal performance varied from the design because of the modeling inaccuracies. This problem exists regardless of the design technique - classical, Riccati optimal gain, LQR, inverse Nyquist, etc. In general, the full potential of digital control for jet engines will not be realized until a adaptive, optimal propulsion system control is achieved that is capable of

(1) Integrated control of the propulsion system
(2) Active identification of the plant to be controlled in real time
(3) Real-time optimization of the control for the identified plant

This paper addresses an orderly, minimum-risk approach to achieving the latter two goals.

The mention of adaptive, optimal control reminds many of the past failures and special problems - especially stability - associated with adaptive controls. Thus, it is necessary to determine a systematic approach to the control development that displays an identifiable gain at each step in order to justify the additional complexity inherent in this system.

The major characteristic proposed here is a building-block control structure leading toward adaptive, optimal control. This approach simplifies the addition of new features and allows for easier checkout of the control by providing a baseline system for comparison. Also, it is possible to eliminate certain features that do not have payoff by being selective in the addition of new "building blocks" to be added to the baseline system.

This is achieved by beginning with a baseline control structure that is easily identifiable with present control systems. The configuration shown in figure 1 features an integrated propulsion system management feature that provides inputs to the engine control management section, like percent thrust required, inlet conditions, etc. The control management section selects the optimal gains, engine schedules, and control schedules for the control laws (classical speed governor, LQR, etc). The control laws issue control commands to minimize an error criterion within the control law. The control commands can

be altered (generally limited) to protect the engine. The signal synthesis and estimation can be simple bandpass filters, Kalman filters, etc. Every digital control includes some degree of control diagnostics to provide mode selection (backup control when a failure occurs as a minimum).

The first step toward adaptive, optimal control is the identification of the plant or engine characteristics, along with the control diagnostics. This step is chosen first because it has payoffs outside the control. Of course engine diagnostics is a many-faceted objective. The philosophy suggested here is simply that engine diagnostics belongs in the control digital computer only to the extent that action is required by the control. This approach minimizes the potential dangers of increased cost, complexity, and weight and reduced reliability introduced by adding engine diagnostics. This must be balanced by the overall reduction in engine weight, cost, and complexity by sharing features between the control and engine diagnostics. Possible actions within the control are

(1) Lower gains
(2) Lower engine parameter upper limits
(3) Operating line moved further from surge for engine stability
(4) Alternative modes

However, most engine diagnostic techniques employed today are not accurate or sensitive enough to generally warrant such an interaction with control. Therefore we proceed one step further to parameter identification, as shown in Figure 2, to provide more diagnostics information and to lay the groundwork for adaptive control. Parameter identification techniques are being developed for both linear and nonlinear models, and the choice will depend mainly on the application. Generally a sequential technique will be employed to provide a real-time, on-line identification process. A filtered-sequential technique is currently favored at DDA because (1) it minimizes large transient effects, (2) it is less sensitive to noise, (3) it generates the required derivatives, and (4) it is well suited to slowly varying parameters that are compatible with current adaptive techniques. The results of parameter identification can be applied to

(1) Signal synthesis and estimation for the control
(2) Engine diagnostics
(3) Adaptive control

and this provides an identifiable payoff even if we fail in the next step - adaptive control.

We define an adaptive control as a control system that senses plant variations and adjusts control parameters to achieve a control objective. The ultimate goal is to provide a control system that continuously adjusts control parameters to achieve optimal engine performance. The term optimal is usually loosely used since it is often difficult to put exact physical significance on what is mathematically optimized to achieve the desired engine performance.

The next step toward adaptive control is to look at what control parameters one might adjust to achieve the desired control performance. The control gains generally only affect the transient behavior of the control, with only a secondary effect on steady-state performance for proportional control. Achieving true optimal gains would generally require an on-line solution to the

Riccati equation. Adjustment of the control schedules has a major influence on the steady-state performance and some effect on the transient behavior (acceleration and deceleration schedules). Here true optimal performance would require on-line optimization of the control schedules - generally a gradient search with multiple constraints. The control designer has little flexibility with the engine limits.

Now we have sensed engine variations and examined those control parameters we can adjust. But what about qualifying "desired engine performance" or "optimization" in this case. Off-line optimization is the most practical approach that can be achieved with today's technology. The steps to achieve this goal are

- Optimize nominal system
- Determine nonnominal models
- Optimize nonnominal systems
- Derive control parameter deviations from nominal
- Express control "trims" in terms of model deviations

The use of control trims reduces the authority of the adaptive process and provides a safe approach. With the development of on-line parameter identification this approach is feasible today.

However, one may wish to consider one further step - the ultimate goal, on-line optimization. This is a big step with many potential problems and must show sizable payoff to offset the risk and complexity. The most feasible approach is linear model optimization with a possible closed-form solution. However, the inaccuracies of the linear model may leave this approach less optimal than the off-line method using a nonlinear model.

On-line optimization of the nonlinear model does not seem practical with today's techniques - especially with the large number of constraints in the engine optimization problem. The on-line optimization of the actual engine through perturbation techniques creates even greater stability concerns. Before one rushes forward into on-line optimization, the potential problems of stability, high computational costs, large range of parameters, and transient effects must be weighed against the potential benefits of

(1) Better performance
(2) Simpler schedules
(3) Automatic failure modes

The final goal is an adaptive optimal propulsion control. The road is a difficult one with many pitfalls. The approach presented here will maximize the probability of success with a building-block structure that promises added payoffs at each step toward the final goal.

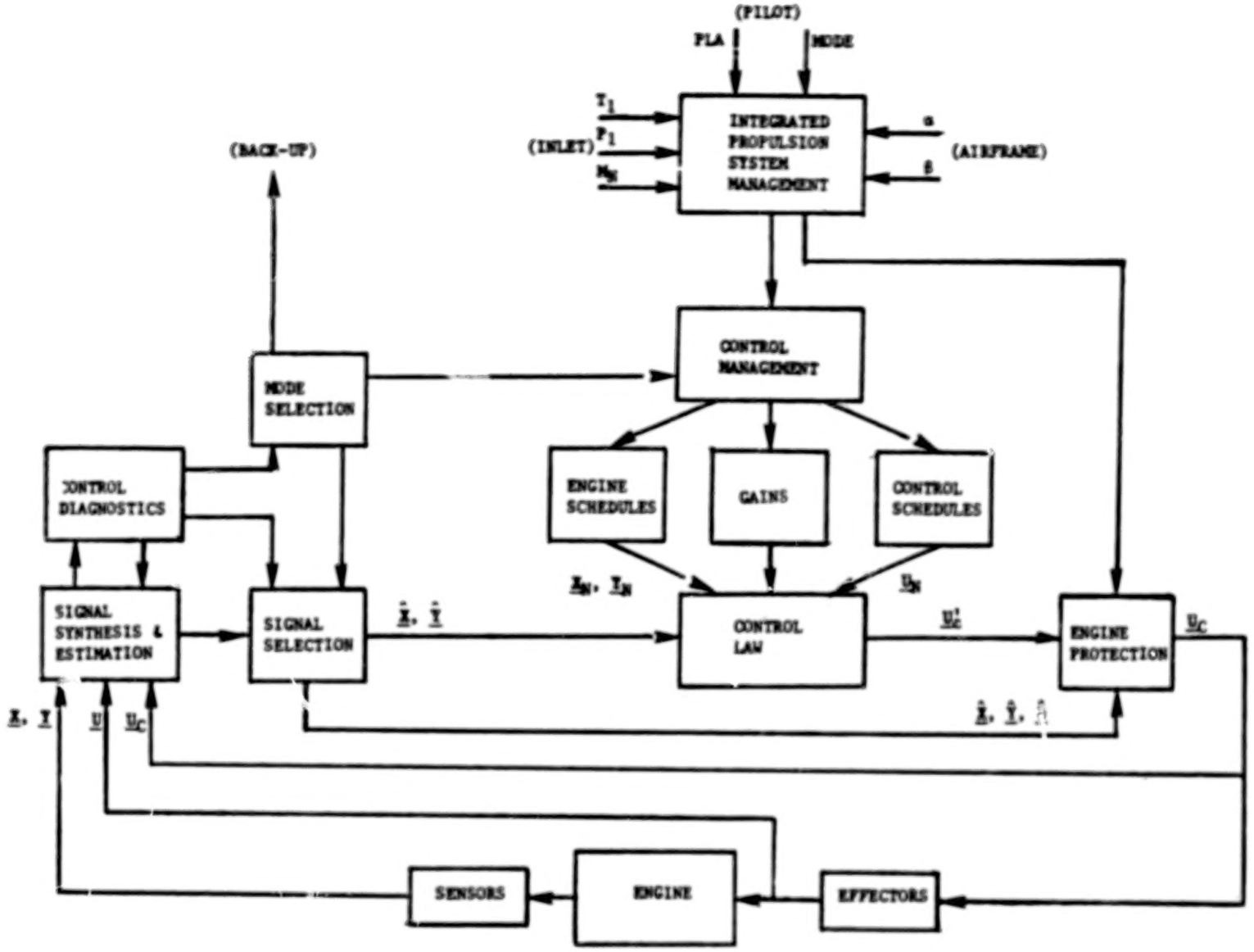


Figure 1. - Current control structure.

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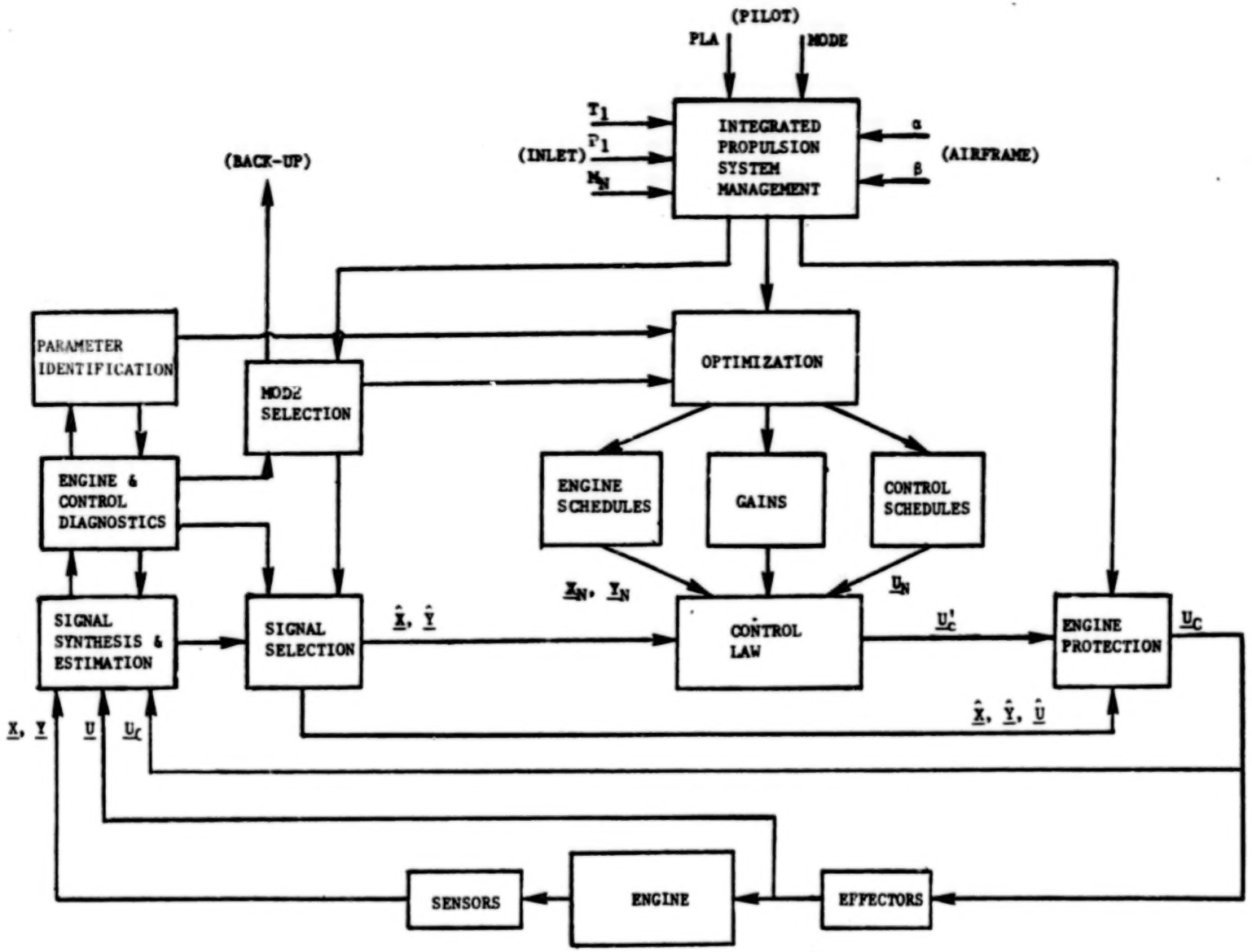


Figure 2. - Adaptive optimal control structure.

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PROPULSION CONTROL AND CONTROL THEORY - A NEW RESEARCH FOCUS

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Aircraft propulsion system designs are increasing in complexity in order to achieve new levels of performance. The performance is being improved in terms of fuel efficiency, thrust-to-weight ratio, and such environmental factors as noise level and emissions. These improved turbine engine powerplants will have more inputs to be manipulated and more parameters to be measured. This fact is demonstrated by the chart of figure 1, which shows the increase in the number of controlled variables for various operational engines. As can be seen, this number has been increasing with time as engines have been improved.

Control systems for these more complex engines will be required to measure a greater number of variables more accurately and then act upon them in order to properly manipulate the multiplicity of inputs to the engine system. The control system, as a result, will be affected in two major areas: First, new rigorous and straightforward methods for designing acceptable control modes for the multiplicity of interacting inputs and outputs will be required. Second, the computational requirements of the new, more accurate control modes will require a digital electronic computing device instead of the present hydromechanical analog type of control computer. To address these two requirements, certain technology advances will be needed. This paper discusses these needs and the role that the NASA Lewis Research Center, as a Government research organization, will play in attacking certain of these needs.

TECHNOLOGY NEEDS

One of the technology needs is methodology for designing control modes for a process (turbine engine) that is both nonlinear and multivariable. Recent advances in analytical control theory offer possible solutions to this problem. In fact, the symposium of which this paper is a part was devoted to discussing how far we have progressed toward being able to rigorously design control laws for modern aircraft engines. Since a number of other papers address this issue quite adequately, no further comments on this multivariable control design problem are made herein. However, some extensions of the theory to satisfy needs beyond control mode selection are discussed later in this paper.

The requirement to replace the computation-limited hydromechanical analog controller being used today with a digital electronic control system is already being addressed in an evolutionary fashion. This is shown by the diagram of figure 2. The highly reliable hydromechanical controls used for relatively simple (from a control standpoint) engines are already being augmented by a supervisory digital electronic control. This arrangement is operational on the F100 turbofan engine used on the F-15 and F-16 military aircraft. Figure 3 is a

cutaway view of this modern engine. The supervisory electronic control is used to trim the operation of the hydromechanical controller. Full performance is only achieved through the use of the supervisory functions. The supervisory control, which is mounted on the side of the engine, is vibration isolated and fuel cooled to enable it to survive in that hostile environment. Similar supervisory units will be used on the future fleet of Boeing 767 commercial aircraft.

The move to full-authority digital controls is being hampered by the reliability concerns surrounding electronic devices operating in the hostile engine environment. In fact, as shown in figure 2, full-authority digital electronic controls may first be used in conjunction with limited-authority hydromechanical backup controllers. Finally, as confidence increases, full-authority electronic controllers with electronic backup or redundancy schemes will come into use.

Figure 4 shows the quantitative levels of reliability concerned with propulsion control devices. Reliability here is measured as the mean time between failures (MTBF). Mature hydromechanical controllers on commercial engines now exhibit about 10 000 to 20 000 hours MTBF. The electronic supervisory control on the F100 engine, however, is down near 800 to 1200 hours MTBF. If this low figure is indicative of where the technology is for turbine-engine mounted electronics, a full-authority electronic control has significant technology needs before it can be accepted into operational service. The need for improvement is even more pronounced for a vertical-takeoff-and-landing (VTOL) aircraft. Flight control reliability requirements are usually an order of magnitude more stringent than those for the propulsion control of a multiengined aircraft. In the VTOL application the sophisticated powerplant will be an integral element of the flight control for the vertical mode of flight. Thus the required electronic propulsion controller will have to meet the same reliability requirements as the flight control (possibly greater than 10^6 hr). Achieving such high reliability with the propulsion control will definitely demand many technology advancements. The next sections describe the role the Lewis Research Center will play in this technology endeavor.

LEWIS PROPULSION CONTROL RESEARCH

The main thrust of the Lewis Research Center propulsion controls research activity then is to develop technology for enhancing the reliability of future aircraft powerplant control systems. In terms of our role as a Government research organization, we will identify the technology opportunities and then concentrate on those that are high risk but potentially offer a high payoff. These are the areas for which industry has difficulty justifying the expenditure of their own research funds. In these areas of opportunity we are talking about technology that would enter into service in the 1990's and beyond.

Figure 5 shows the technology opportunities as we perceive them for enhancing the reliability of future propulsion control systems. As shown in the figure the major elements making up an advanced control fall into four categories: (1) sensors and actuators, (2) computer, (3) control modes and software, and (4) power sources. Power sources is an important area of technology needing advances. However, because of limited resources it is not being pursued by Lewis. The remaining three categories, however, each have activity being pur-

sued by Lewis. A brief comment on each of the subcategories of figure 5 will be made, with heavier emphasis on those areas pertaining to some aspect of control theory or analytical methods.

In the sensor and actuator category, work is being pursued to minimize the problems associated with merging the real analog world that must be sensed and acted upon with the digital computations of the control. Sensors are being developed that will have outputs which can more easily be accepted by the digital computer, thus simplifying the interface complexity. In addition, the potential advantages of optical devices are being explored in hopes of operating more reliably in high electrical noise environments and/or in high-temperature situations.

In the computer category, a careful look is being taken at the potential that very large-scale, integrated (VLSI) circuit components have in enhancing reliability. The areas include the use of multiple processors either redundantly or in some modular reconfiguration scheme to achieve a fault-tolerant control computer. Also being pursued is the viability of optical computers as a possible candidate for the hostile engine environment. This, however, is a long-range technology that is not expected to mature for quite some time.

The category of control modes and software is most closely related to the items that were the central theme of the 1979 Propulsion Controls Symposium. As stated earlier a number of linear multivariable design techniques have been studied in relation to their applicability to the turbine engine control problem. These include both time domain and frequency domain approaches. Some have been extensively investigated, such as the linear quadratic regulator (LQR) approach used in the F100 MVCS program. Others have not been so exhaustively evaluated.

FUTURE LEWIS CONTROL THEORY RESEARCH

Future efforts in multivariable design sponsored by Lewis will concentrate on nonlinear design techniques. The intent is to avoid the somewhat tedious or cumbersome design methodology based strictly on linear techniques. Linear operating-point designs require some intelligent way to tie together a family of linear control designs based on a series of well-defined operating points. A nonlinear, multivariable methodology could simplify the control design task by requiring just one design or, at least, by minimizing the number of operating-point designs.

To make use of redundant or reconfigurable hardware architectures, reliable, fault-tolerant software algorithms must be studied. Along with that will be work on sensor-actuator failure detection, isolation, and accommodation algorithms. Success of this technology depends upon the inherent computational power of the computer to minimize the redundancy requirements on critical sensors and actuators.

Much of the failure accommodation work will be based on principles of system identification. Identification techniques permit the parameters of analytical models to be determined for the system being identified. These models can

be identified from data obtained from experiments or from exercising a simulation of the process in question. Models are necessary to make use of rigorous control design procedures as well as to determine failures of system components. Effort will be directed toward improving the accuracy of identification techniques and enhancing the capability of identifying in real time. These improvements will allow for the future use of adaptive control strategies.

CONCLUDING REMARKS

In summary, then, it should be reiterated that there are a number of technology needs before reliable digital control of advanced aircraft powerplants can become a reality. A number of these needs are being pursued under Lewis Research Center direction. In the specific area of control theory research, emphasis is on simplified control design procedures and on software that will guarantee reliable operation even under conditions of component failures. This work will continue through a combination of university grants, contracts with industry, and in-house evaluations.

TRENDS IN CONTROL COMPLEXITY

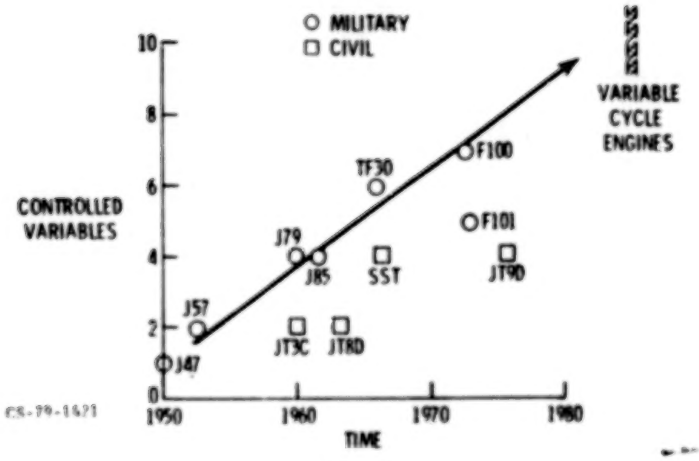


Figure 1

EVOLUTION OF ENGINE CONTROLS

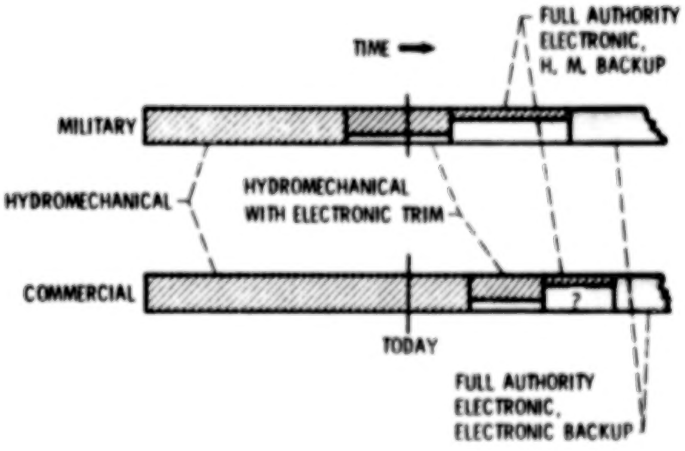


Figure 2

F100-PW-100 TURBOFAN ENGINE

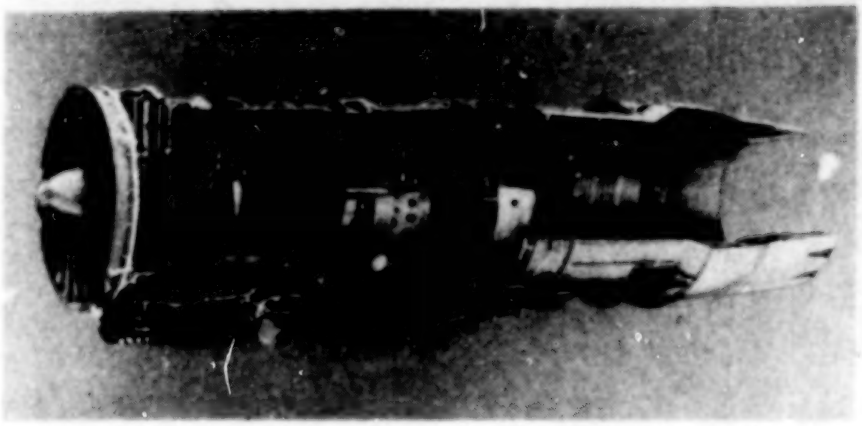


Figure 3

CONTROL SYSTEM RELIABILITY



Figure 4

CATEGORIES OF TECHNOLOGY OPPORTUNITIES

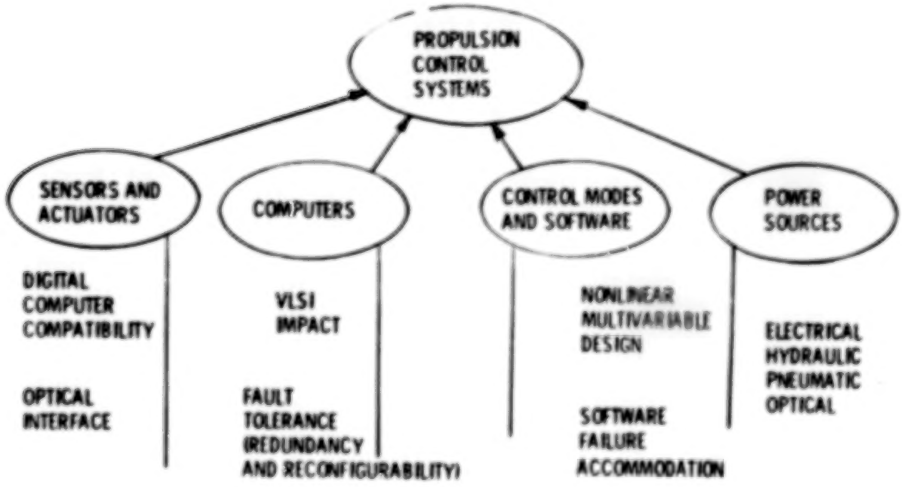


Figure 5

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ENGINE IDENTIFICATION FOR ADAPTIVE CONTROL*

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SUMMARY

This paper describes an attempt to obtain a dynamic model for a turbofan gas turbine engine for the purpose of adaptive control. The requirements for adaptive control indicate that a dynamic model should be identified from data sampled during engine operation. The dynamic model identified was of the form of linear differential equations with time-varying coefficients. A turbine engine is, however, a highly nonlinear system, so the identified model would be valid only over a small area near the operating point, thus requiring frequent updating of the coefficients in the model. Therefore it is necessary that the identifier use only recent information to perform its function. The identifier selected minimized the square of the equation errors. Known linear systems were used to test the characteristics of the identifier. It was found that the performance was dependent on the number of data points used in the computations and upon the time interval over which the data points were obtained. Preliminary results using an engine deck for the QCSEE indicated that the identified model predicted the engine motion well when there was sufficient dynamic information, that is when the engine was in transient operation.

INTRODUCTION

Identification is an essential part of any adaptive control strategy. It is necessary to determine the current performance characteristics of a plant in order to adaptively modify the overall system to better satisfy a given performance index. The work described herein focused upon the development of identification techniques which have characteristics suitable for use as part of an adaptive control system. A detailed description of this work is available in reference 1.

*Sponsored by NASA Lewis Research Center Grant NSG3119.

DESCRIPTION OF THE METHOD

The method is illustrated by applying the technique to a simple second order system described by

$$\ddot{x} + a\dot{x} + bx = cu$$

The objective is to identify the coefficients a, b, and c from measurements of the input, u, and output, x, as well as measurement or computation of the derivatives, $\dot{x}$ and $\ddot{x}$. An error, e, is defined and forms the basis for an equation error identification scheme

$$e = \hat{c}u = \ddot{x} - \hat{a}\dot{x} - \hat{b}x$$

where $\hat{a}$ denotes the estimated or identified value of the coefficient a. The estimates are chosen such that for N discrete samples, the index of performance

$$IP = \frac{1}{2} \sum_{i=1}^{N} e_i^2$$

is minimized to provide best values of the coefficients in a least squares sense. Partial derivatives are taken with respect to each coefficient which yield

$$\frac{\partial IP}{\partial \hat{a}} = \sum_{i=1}^{N} e_i \frac{\partial e_i}{\partial \hat{a}} = 0$$

$$= \sum_{i=1}^{N} e_i \dot{x}_i = 0$$

or

$$\sum_{i=1}^{N} (\hat{c}u - \ddot{x} - \hat{a}\dot{x} - \hat{b}x)_i \dot{x}_i = 0$$

Evaluating the other partial derivatives and performing some rearrangement gives the vector equation

$$\begin{bmatrix} -\hat{a} \\ -\hat{b} \\ \hat{c} \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} \dot{x}_i^2 & \sum_{i=1}^{N} \dot{x}_i x_i & \sum_{i=1}^{N} \dot{x}_i u_i \\ \sum_{i=1}^{N} \dot{x}_i x_i & \sum_{i=1}^{N} x_i^2 & \sum_{i=1}^{N} x_i u_i \\ \sum_{i=1}^{N} \dot{x}_i u_i & \sum_{i=1}^{N} x_i u_i & \sum_{i=1}^{N} u_i^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=1}^{N} \ddot{x}_i u_i \\ \sum_{i=1}^{N} \ddot{x}_i x_i \\ \sum_{i=1}^{N} \ddot{x}_i \dot{x}_i \end{bmatrix}$$

The symmetry of the matrix on the right-hand side (aided by the negation of $\hat{a}$ and $\hat{b}$) is attractive for the required inversion.

The method can be utilized off-line where many samples from operating records can be used in the summations. Previous investigations (2, 3) have successfully used this method to identify parameters in dynamic systems. A more challenging use for the method lies in on-line applications. The most challenging application is in the area of adaptive control where it is essential to obtain a description (model) of the system in real time so that the adaptation can be effected.

To employ this identification scheme in real-time the practitioner must make three choices:

1. a model form whose coefficients are to be determined
2. a sampling interval, Δt, between the times when the input, output, and required derivatives are sampled
3. the number of samples, N, which are to be used by the identification algorithm.

AN ILLUSTRATIVE EXAMPLE

The method was applied to a known system described by the differential equations

$$\dot{x}_1 = ax_1 + bx_2$$

$$\dot{x}_2 = cx_1 + dx_2 + u$$

with two fixed coefficients, a = 0, b = 1, and with the coefficients c and d being time varying. The input, u, was a square wave. The identification

technique was used to identify these four coefficients. [A generalization of the technique for multiple input/multiple output systems is presented in (1)].

Figures 1 through 4 show the results from four of the test cases that were conducted to illustrate the nature of the method. In figure 1 it can be seen that the actual coefficient c varies linearly with time while d varies in a sinusoidal fashion. Note also that the coefficients vary slowly compared to the period of the input square wave which is 0.5 seconds. The identified values for c and d do a reasonably good job of tracking the actual parameter values in figures 1, 2, and 3. In figure 1 the identification window, $N\Delta t$, is 0.8 seconds and the identified values tend to follow approximately half of this time behind the actual values. The identification window is doubled in figure 2 by retaining 16 data points for the identification rather than 8. The time lag between the actual and the identified coefficients is again approximately half of the identification window. Figure 3 illustrates the use of a smaller time interval, 0.05 seconds as compared with 0.1 seconds in figures 1 and 2, to reduce the identification window. The results shown in figure 3 are identical to those of figure 1 where both identification windows are 0.8 seconds.

Figure 4 illustrates the degradation of performance which results when insufficient information is provided for identification. For this case the input period was increased to 4 seconds, the approximate settling time of the system being identified. With this slow input the system approaches steady state before the input square ware changes state. As the system approaches steady state, the derivative terms required in the identification algorithm approach zero and numerical difficulties are encountered adversely affecting the computed values for c and d. Immediately following the reversal of the input, the algorithm quickly recovers and moves toward the correct result but the lack of sufficient dynamic information precludes the attainment of satisfactory identification. With this lack of dynamic information no combination of sampling interval and number of data points will produce satisfactory results. If such a condition was encountered in practice, a number of alternatives could be employed including suspension of the parameter identification while retaining previous results. Another possibility would be to change the model form for the identification to a lower order, possibly even a static model, until sufficient dynamic information is again available for use.

APPLICATION OF THE METHOD TO A TURBINE ENGINE MODEL

Engine performance data were obtained from a digital simulation of the QCSEE (Quiet, Clean, Shorthaul Experimental Engine). This simulation includes a 16th order model (including sensors and actuators) and the nonlinearities for such items as the compressor maps based upon curve fits to typical engine characteristics.

One of the objectives of this preliminary work was to obtain reduced order linear models, probably with time-varying coefficients, which could be used to

describe the engine. It was felt that these models would be applicable about an operating point and that they may be capable (with suitable identification) to track the engine under transient conditions. Initial efforts were tried using a second-order model to account for the two spool speeds in the QCSEE since it was felt that these would be the dominant energy storage elements. These attempts were not fruitful. It was necessary to add a third state, the compressor outlet temperature, to "account" for a thermal energy storage.

Some promising results were obtained with a third-order model using as states the compressor spool speed, NH, the fan spool speed, NL, and the compressor exit temperature, T3. The three inputs to the engine, fuel flow, WFM, fan blade angle, BETA, and the fan nozzle exhaust area, A18, formed the input vector. The engine was excited by a ramp variation in the power level angle from 40° to 45° to 40° over a period of one second. Figure 5 shows the result from one of these preliminary runs. The plots show the variations of the three eigenvalues associated with the state variables. As expected the dominant (slowest) eigenvalue is associated with the fan spool speed and the fastest is associated with the thermal state variable. While no actual verification of the numerical values obtained from the identification has been made, the trends and approximate magnitudes of the results are encouraging.

CONCLUSION

The identification method appears promising for utilization in an adaptive control strategy. The algorithm is attractive for implementation on an onboard computer if models of low order can be used to adequately describe the engine dynamics. No attempt has been made to date to examine a combination of scheduled gains with adaptive trim which may be necessary to follow rapid acceleration/deceleration transients or to operate the system in the absence of adequate dynamic information.

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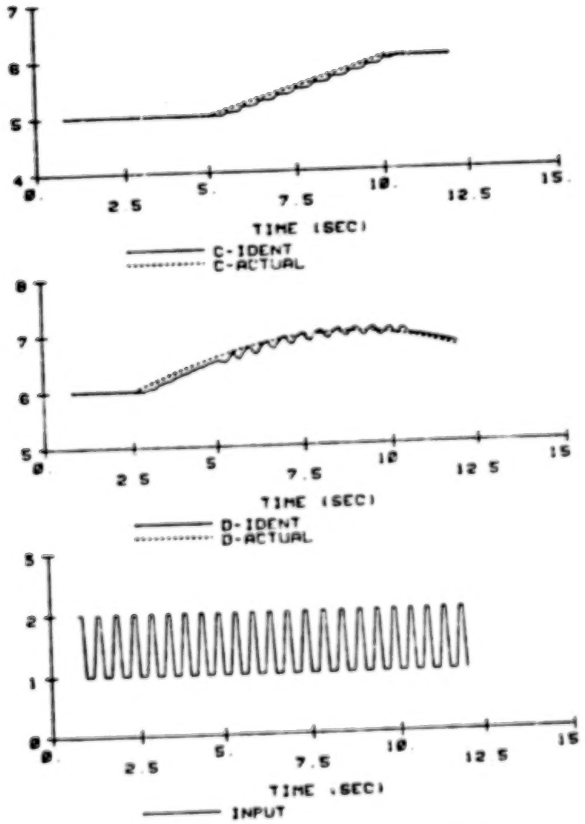


Figure 1. - Identified and actual coefficients for known system with $\Delta t = 0.1$ and $N = 8$.

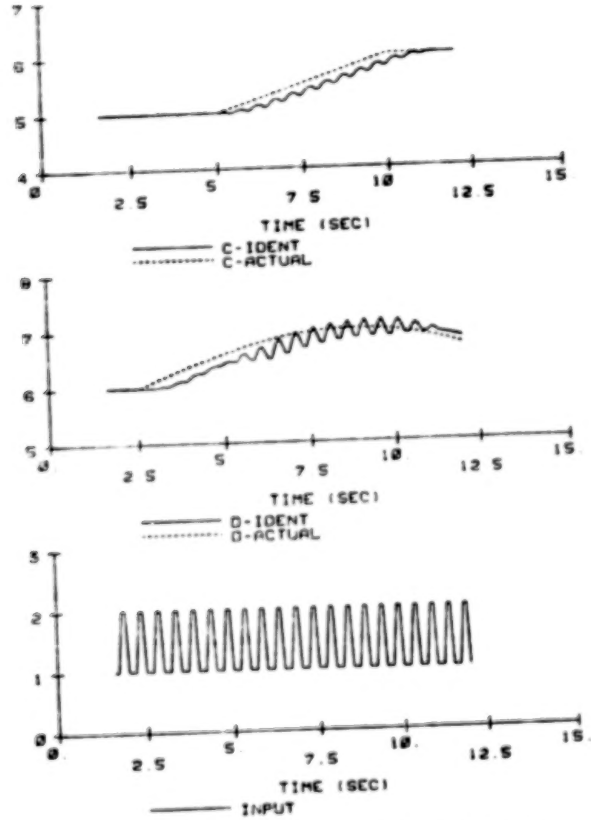


Figure 2. - Identified and actual coefficients for known system with $\Delta t = 0.1$ and $N = 16$.

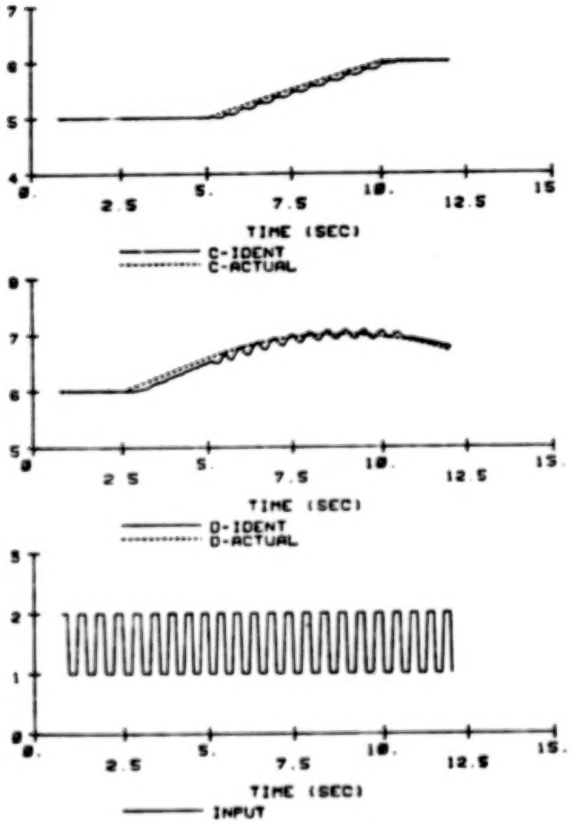


Figure 3. - Identified and actual coefficients for known system with $\Delta t = 0.05$ and $N = 16$.

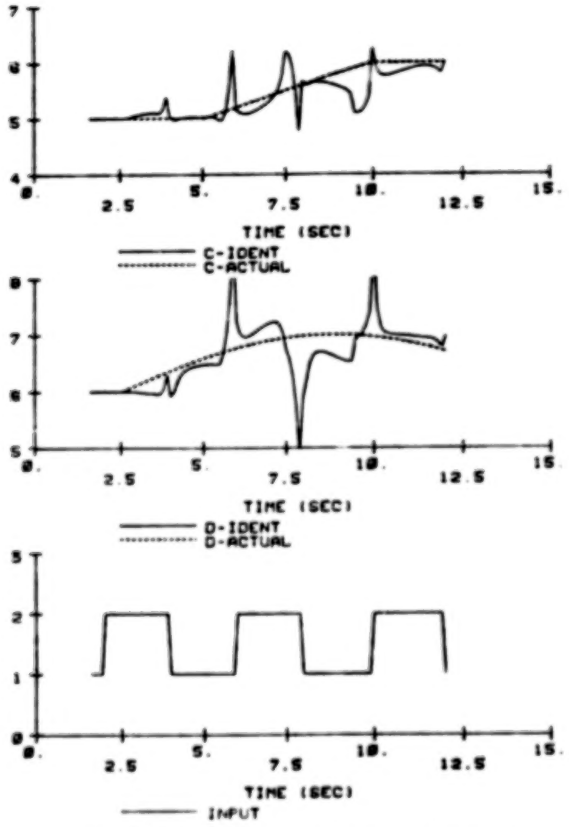


Figure 4. - Identified and actual coefficients for known system with $\Delta t = 0.1$ and $N = 16$.

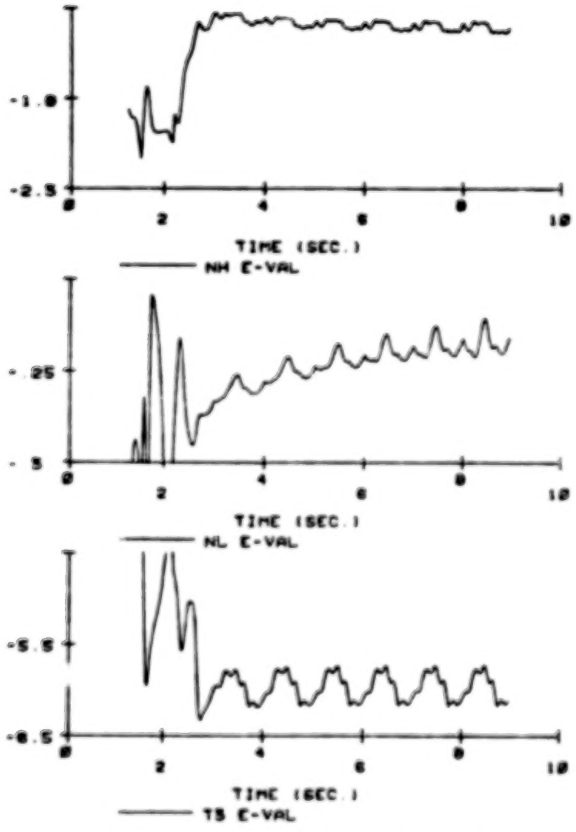


Figure 5. - Eigenvalues as a function of time.

MULTIVARIABLE NYQUEST ARRAY METHOD WITH APPLICATION TO TURBOFAN ENGINE CONTROL

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SUMMARY

Recent extensions to the multivariable Nyquist array (MNA) method are used to design a feedback control system for the General Electric-NASA Quiet Clean Shorthaul Experimental Engine (QCSEE). The results of this design are compared with those obtained from the deployment of the General Electric control system design on a full scale non-linear, real-time digital simulation. The results of this research program clearly demonstrate the utility of the MNA synthesis procedures for highly non-linear sophisticated design applications.

The QCSEE turbofan engine was developed by the General Electric Corporation under contract to the NASA Lewis Research Center during the period 1974-1978. The design incorporates performance and structural characteristics unlike those in any engine in production today and includes

1. An extremely high by-pass ratio and a high throat Mach number inlet for noise suppression

2. Reversible pitch fan blades for rapid thrust response (0.8 seconds from approach to full power)

3. Geared turbine/fan combinations for low fan speeds with a high thrust rating

4. Digital electronic engine contols

5. Extensive use of composites for drag reduction and weight considerations

To incorporate all five characteristics into a single propulsion system represents a significant breakthrough in turbofan engine technology. During 1978-1979, the QCSEE engine was successfully tested at the NASA Lewis test facility.

During this period of development and testing of the QCSEE engine, NASA developed a highly non-linear accurate real-time digital simulation of the engine at sea-level static conditions. This non-linear model was used in extensive tests at the NASA Ames in-flight simulator facility for test pilot evaluations of integrated engine airframe combinations [1].

Using the non-linear simulation, a set of transfer function matrices were generated for each of five power lever settings covering the range from approach power to full power, i.e., 62.5% to 100%. The method used to obtain the linear models is identical to that used in the F/100 study. Step response comparison of the linear models with the non-linear QCSEE simulation validated the models at each operating point.

For the QCSEE engine, there are three manipulated variables (inputs): fuel flow, nozzle area, and fan blade pitch angle. The measurable outputs for transfer function evaluation were selected to be: fan speed, inlet duct pressure (P_{12}), and combustor exit pressure (P_4). Inlet duct pressure control provides an indirect control over inlet Mach number for noise suppression while combustor exit pressure control provides a control of engine thrust response.

With the inputs and manipulated outputs identified above, an extensive control synthesis program was executed using the multivariable Nyquist array (MNA) method [2,3,4] and the recent extensions to multivariable Bode diagrams (MBD) and Nichols charts (MNC) [5,6,7]. The QCSEE design was initially performed holding nozzle area full open with fixed fan blade pitch angle at a power setting of 62.5% of full power. The control design was then evaluated at other power settings and tested in the non-linear simulation to evaluate engine performance during a power slam from 62.5% to full power (100%). Non-linear simulation transients were then compared with the full scale General Electric control time response.

The General Electric control design is based upon a series of single input, single output design evaluations with loop interactions accounted for qualitatively rather than quantitatively [8]. In the actual implementation of this control, the manipulated input variables are scheduled according to engine operating environment. In a power slam mode fuel flow is the only variable input over the 62.5% to 80% power range. At 80% power, fan pitch angle is activated and a two input situation is in operation. At the power level of 90% exit nozzle area is activated and a three input situation arises until full power is achieved. All MNA design simulations were compared with time responses resulting from this GE control.

The next phase of the MNA design program used fuel flow and fan pitch angle as inputs with fan speed and combustor exit pressure as the measured outputs. Nozzle area was again held to a fixed open position. Using the MNA method with the Bode and Nichols options, control systems were synthesized for the two input, two output models. It was established that a fixed control configuration could be used over the power lever range previously indicated. This control unit was then applied to the non-linear simulation and compared with the GE control responses. The significant result established at this point was that fan pitch angle (and fuel flow) can be used effectively at low

power settings without violating the physical constraints. It provides for a rapid thrust response with a significant lower expenditure of total fuel consumption.

The results of the two input, two output case above were extended to the three input-three output system with nozzle area as the third input. This input variable is used to provide additional control over inlet Mach number with inlet duct pressure as the third output variable. System dominance was easily obtained at each power setting with closed loop system performance designed using the multivariable Bode diagrams. Non-linear simulation results of the MNA control are compared with those obtained from the GE control. A representative comparison is provided in the accompanying figures.

The dashed curve in each of the figures represents the time response of the non-linear simulation to the General Electric control under a step power demand from 62.5% of full power to 100% full power. The solid curves represent the corresponding results using the control design obtained from the multivariable Nyquist array method.

The MNA design was obtained through the following procedure:

Step 1. Determine linear state space models and system transfer functions about the steady state operating points of the non-linear simulation with the GE control and related control constraints disengaged.

Step 2. Using [7] obtain diagonal dominance. (Nominally 2 CPU minutes on a PDP 11/70)

Step 3. Evaluate performance in each control loop using [6].

Step 4. Insert MNA control into non-linear simulation to evaluate time responses.

Step 5. Overlay GE and MNA control responses.

In addition to the control design for the QCSEE engine the MNA method has also been successfully applied to the F 100 turbofan engine [4].

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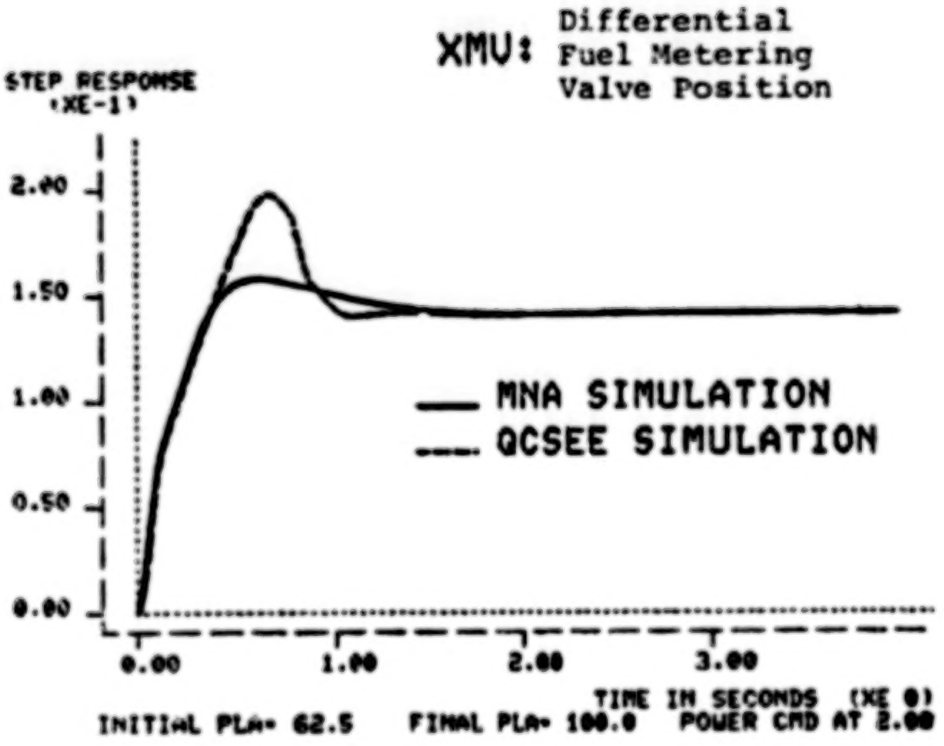
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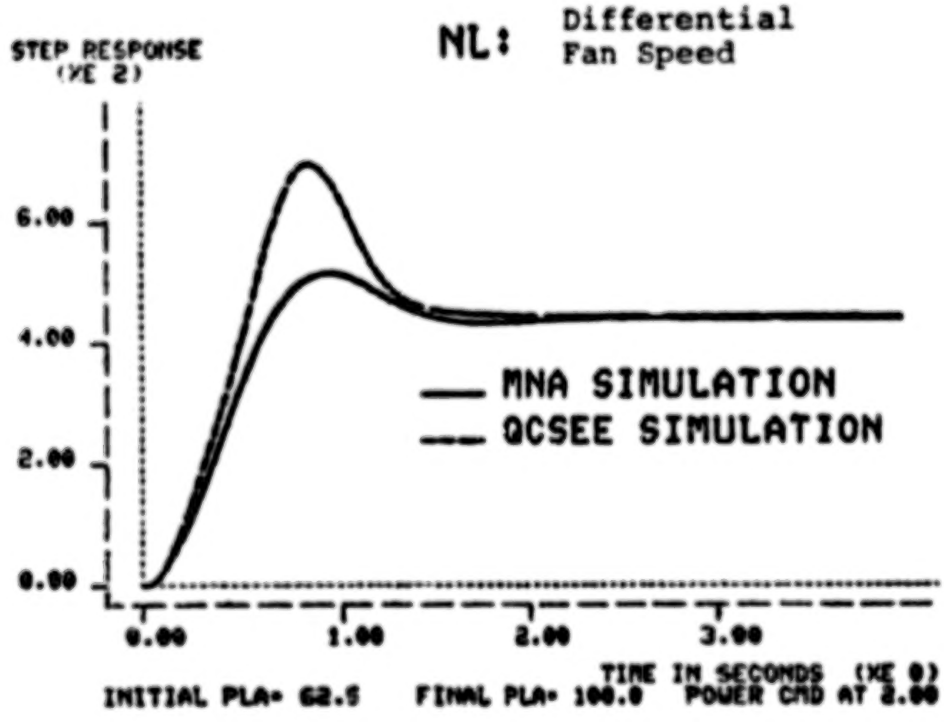
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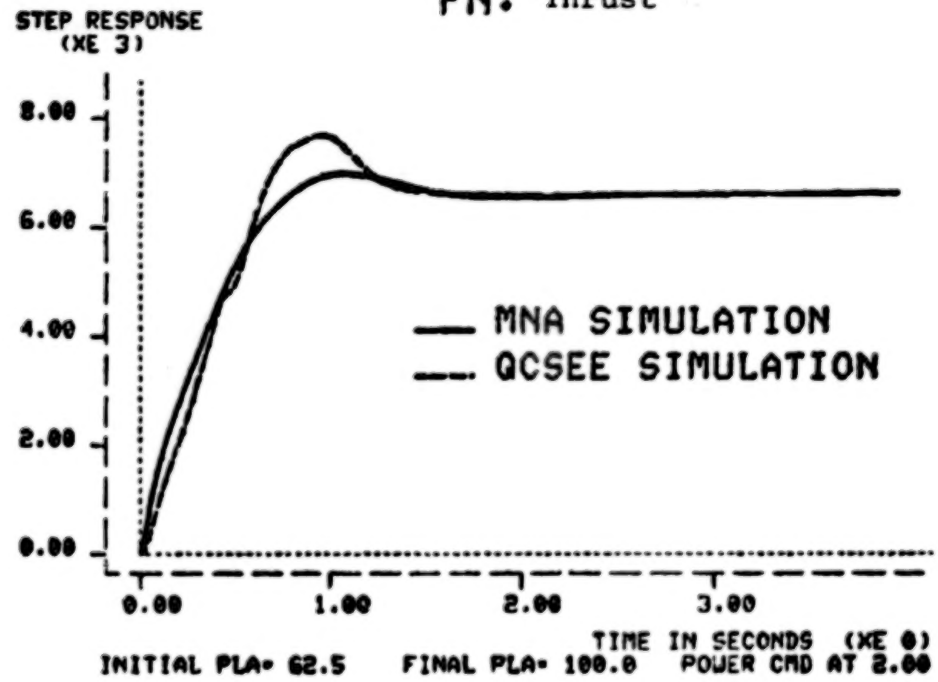
7. Leininger, G. G., "An Interactive Design Suite for the Multivariable Nyquist Array Method," Ibid, pp. 305-330.

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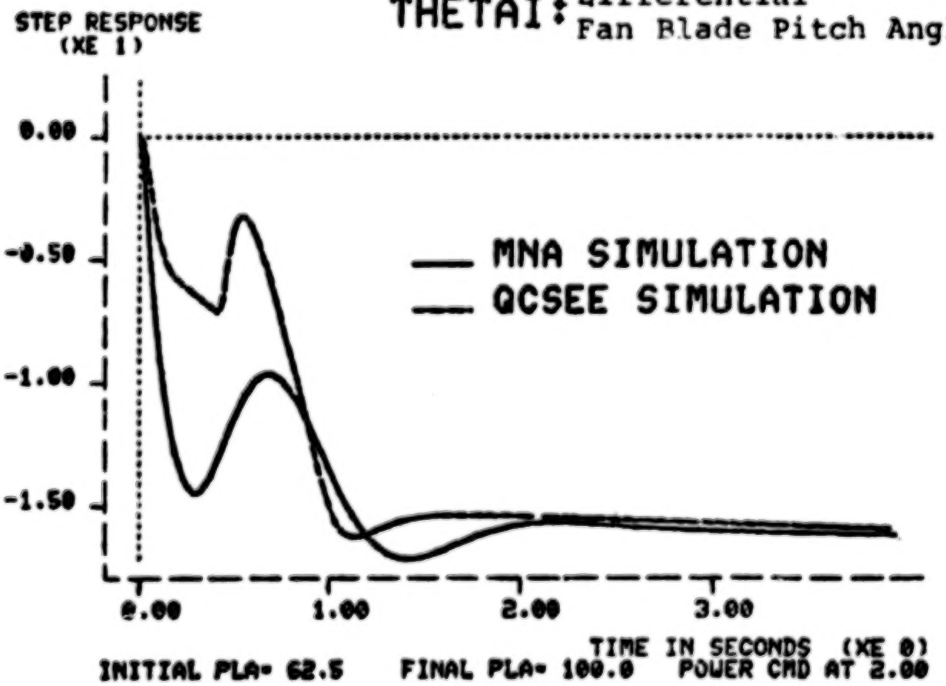

XMU: Differential Fuel Metering Valve Position
STEP RESPONSE (XE-1)
2.00
1.50
1.00
0.50
0.00
0.00
1.00
2.00
3.00
TIME IN SECONDS (XE 0)
MNA SIMULATION
QCSEE SIMULATION
INITIAL PLA= 62.5
FINAL PLA= 100.0
POWER CMD AT 2.00


NL: Differential Fan Speed
STEP RESPONSE (XE 2)
6.00
4.00
2.00
0.00
0.00
1.00
2.00
3.00
TIME IN SECONDS (XE 0)
MNA SIMULATION
QCSEE SIMULATION
INITIAL PLA= 62.5
FINAL PLA= 100.0
POWER CMD AT 2.00

FN: Differential Thrust



THETAI: Differential Fan Blade Pitch Angle



MULTIVARIABLE SYNTHESIS WITH TRANSFER FUNCTIONS

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Bendix Energy Controls Division

ABSTRACT

A transfer function design theory for multivariable control synthesis is highlighted. The use of unique transfer function matrices and two simple, basic relationships - a synthesis equation and a design equation - are presented and illustrated. The basic idea of the method is straightforward, easy to understand and easy to apply.

This multivariable transfer function approach provides the designer with a capability to specify directly desired dynamic relationships between command variables and controlled or response variables. At the same time, insight and influence over response, simplifications and internal stability is afforded by the method. A general, comprehensive multivariable synthesis capability is indicated including nonminimum phase and unstable plants. Gas turbine engine examples are used to illustrate the ideas and method.

INTRODUCTION

The concept of transfer function has been a mainstay of control engineering and design. A primary motivation to use transfer functions for multivariable design is to increase insight, choices and simplifications so that a designer may interact with multivariable systems in a more direct and integrated manner. The multivariable transfer function idea was applied to jet engine control by Boksenbom and Hood (1) and Feder and Hood (2) about mid-century. Practical computation with transfer function matrices was a difficult issue at that time; and, the question of how to extend performance specifications to matrices of transfer functions posed another difficulty which is still not completely resolved. In this paper, the use of transfer functions for design of controller dynamics for linear multivariable models of turbine engines is reexamined.

Control system design methods in the frequency domain traditionally have been of two types. In the first type, the designer works indirectly to adjust open loop characteristics so that, when the loop is closed, an acceptable system results. In the second type, the designer works directly from the closed loop specifications

to the specific controller dynamics required. We refer here to this second type method as a synthesis method. A classical discussion of both methodologies may be found in Truxal (3).

Two multivariable transfer function system relationships are derived- a design equation and a synthesis equation. The synthesis equation is used to display internally stable closed loop response possibilities; the design equation is used to compute and simplify explicit controller dynamics. Gas turbine engine examples illustrate ideas and methodology.

MULTIVARIABLE CONTROL SYNTHESIS

The basic notion of multivariable control synthesis with transfer functions is straightforward and easy to understand. Consider Figure 1, a block diagram for a unity negative feedback multivariable structure with no disturbances. References, error, plant input and plant output are designated r, e, u and y respectively. Assume the plant has equal numbers of inputs and outputs, thus P(s) is a square matrix of transfer functions. This assumption is not nearly as restrictive as one might suppose at the outset. More on this later. The controller G(s) is also square.

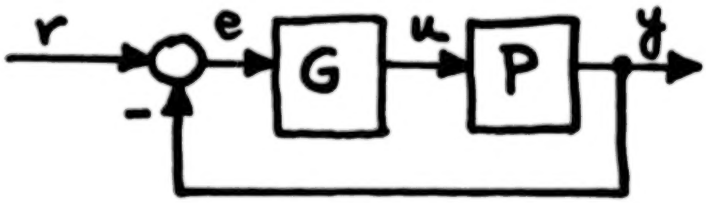


Figure 1. Unity Feedback Structure

The problem is, given plant P(s), to design a controller G(s) to achieve desired, internally stable, closed loop response T(s) as indicated in Figure 2. The objective is to design G(s) so that closed loop response T(s) is achieved in such a way that designer choices, insight and influence are made available and remain accessible. References (4) and (5) can provide more details for the interested reader.



Figure 2. Desired Response

A Design Equation

From Figure 1, the total response of the unity feedback loop is

$$y = PG\,(I + PG)^{-1} r \tag{1}$$

The desired response is

$$y = T\,r \tag{2}$$

Combining equations (1) and (2) and solving for G(s) gives the controller

$$G = P^{-1} T\,(I - T)^{-1} \tag{3}$$

This equation may be written in a convenient, compact form

$$G = P^{-1} Q \tag{4}$$

where Q, a performance matrix, is defined by $Q = T\,(I - T)^{-1}$. Equation (4) is named the design equation for controllers G(s) under the unity feedback structure of Figure 1. The design equation simply and clearly indicates that controller design focuses upon the properties of the plant inverse, $P(s)^{-1}$, and how they interact with Q(s), the performance matrix.

For a unity feedback structure as in Figure 1, and the case of decoupled response forms where the response matrix T is diagonal, a Q-T transform table conventently exhibits elements of the performance matrix, q_{ii}, corresponding to given elements of the response matrix, t_{ii}. Table I lists some standard response forms and related performance element forms for unity feedback loop structures.

TABLE 1

A Q vs. T Transform Table - Unity Feedback, Decoupled Response

DESIRED $t_{ii}(s)$	$q_{ii}(s)$
$\frac{1}{Ts+1}$	$\frac{1}{Ts}$
$\frac{1}{(T_1 s+1)(T_2 s+1)}$	$\frac{1/(T_1+T_2)}{\left(\frac{T_1 T_2}{T_1+T_2}\right)s+1}$
$\frac{W_n^2}{s^2+2\zeta W_n s+W_n^2}$	$\frac{K}{s(Ts+1)}$; $K = W_n/2\zeta$, $T = 1/s\zeta W_n$
$\frac{1}{(T_1 s+1)(T_2 s+1)(T_3 s+1)}$ $T_1 \quad T_2 \quad T_3$	$\frac{1/(T_1+T_2+T_3)}{s\left(\left(\frac{T_1 T_2}{T_1 T_2 T_3}\right)s+1\right)(T_3 s+1)}$

More General Feedback Structure

To effect control of a plant it is necessary to use actuators to drive inputs and to use sensors to measure outputs. Moreover, sensors and actuators can introduce significant dynamical effects into signal paths of the loop. Therefore, a more general feedback structure, which accommodates these effects, is shown in Figure 3.

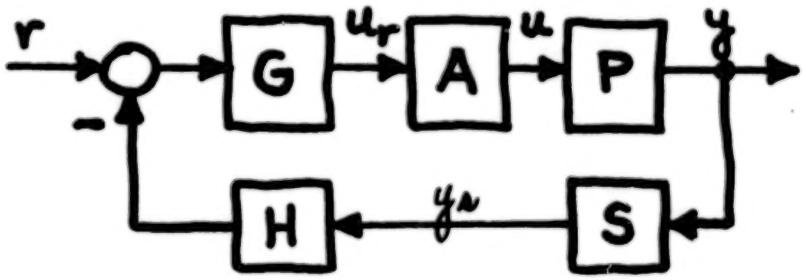


Figure 3 General Feedback Loop

A(s) and S(s) are diagonal actuator and sensor matrices, respectively. The output y is sensed and becomes y_S; the input request, u_r, commands the actuators to produce the plant input, u.

From Figure 3, overall response of the loop is

$$y = (I + PAGHS)^{-1} PAG \; r \tag{5}$$

The desired response is

$$y = T \; r \tag{6}$$

Combining equations (5) and (6) and solving for the controller G

$$G = A^{-1} P^{-1} T (I - HST)^{-1} \tag{7}$$

A performance matrix

$$Q = T (I - HST)^{-1} \tag{8}$$

is easily identified. The design equation becomes

$$G = A^{-1} P^{-1} Q \tag{9}$$

This is a design equation for feedback systems depicted in Figure 3 with the performance matrix Q per equation (8). Equation (9) is a generalization of equation (4); controller dynamics are determined by the characteristics of the actuated plant inverse, $(PA)^{-1}$, and the performance matrix, Q. The plant inverse transfer function matrix is a key element in the design equation. What about the existence of the plant inverse? Is this a serious restriction to transfer function design?

The Plant Inverse

Fortunately, the need for existence of the plant inverse turns out to be not a significant limitation of the design equation. Rather, we can indicate to the contrary that the plant inverse establishes and displays vital plant characteristics needed to effect successful closed loop control design. Four system and plant features, essential for design, are established and identified by the plant inverse transfer function:

1. meaningful multivariable control (6)
2. plant trackability (8)
3. multivariable plant zeros (9)
4. cancellations and simplifications

Rekasius (6) and Wonham and Morse (7) have shown that if the number of plant inputs equals the numbers of its outputs and if P(s) is full rank, i.e., $P(s)^{-1}$ exists, then one has both a meaningful multivariable control problem and necessary and sufficient conditions for existence of a physically realizeable controller that decouples the system. If the number of plant outputs is greater than the number of its inputs, some of the outputs cannot be controlled independently. Even if the number of plant inputs exceeds the number of its outputs, independent control of all outputs is not possible if the plant transfer function matrix, P(s) is not full rank (6).

R. J. Leake, et al (8) define a step trackable linear multivariable plant as one which can asymptotically achieve any constant steady-state output with a bounded control. It is shown that step trackability for proper rational continuous square plants is equivalent to the conditions that:

1. the plant is invertible
2. the plant has no multivariable zeros at the origin ($s = 0$)

Leake goes on to show the significance of step trackability by demonstrating that internally stable, decoupled closed loop design is possible if and only if the plant is step trackable.

Importantly, the multivariable zeros of a plant, P(s), are the poles of the inverse, $P(s)^{-1}$, Wyman and Sain (9). Therefore, multivariable plant zeros are readily identified from the factored form of the inverse transfer function matrix.

Thus, existence of the plant inverse assures conditions needed to effect design. Moreever, the plant inverse matrix provides essential design information about plant trackability, about plant multivariable zeros and about existence of meaningful and internally stable closed loop control realizations.

A Synthesis Equation

Little has been said about loop stability. From another view of the problem of synthesis of closed loop controllers, a synthesis equation will be derived which can be used to establish existence of internally stable closed loop controllers. The synthesis equation was first proposed by Dr. R. J. Leake of Fresno State. Connection of the equation to current system theory (10) and internal stability was made by Dr. M. K. Sain of Notre Dame. The author is happy to acknowledge continuing collaborations and discussions with Professors Sain and Leake on multivariable synthesis with transfer functions.

Consider Figure 4 where r denotes request, u denotes control action, and y denotes response. Under broad assumptions, there exist linear operators T: R→Y

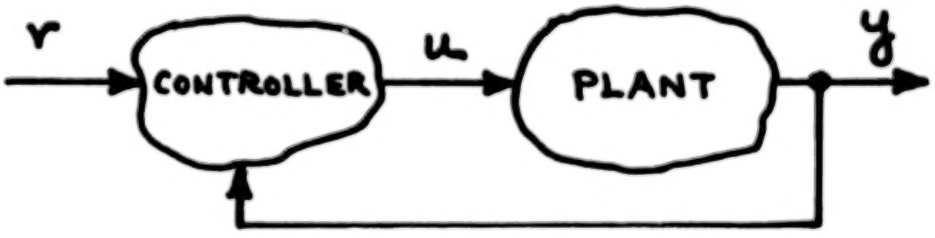


Figure 4 A General Control System

and M: R→U, where R, U, and Y may be understood as R(s)-vector spaces of finite dimension such that (5)

$$y = T\,r,\quad u = M\,r \tag{10}$$

The plant can be understood in terms of an operator P: U→Y, such that

$$y = P\,u \tag{11}$$

Combining equations (10) and (11) obtains the relationship

$$T = P\,M \tag{12}$$

Bengtsson(10) proves that internally stable feedback realizations of systems depicted by Figure 4 exist if any only if M is proper and stable and T is proper and stable.

Imposing a tracking requirement, as for example that y should asymptotically track step responses, then P must be epic. If in addition the number of inputs equals the number of outputs, then P is monic also. Therefore, we can address an inverse total synthesis problem (ITSP) (5) which is governed by the synthesis equation

$$M = P^{-1} T \tag{13}$$

Note that equation (13) is similar in form to design equation (4) or (9).

Two Basic Equations

Two equations form a basis for multivariable synthesis with transfer functions:

- the synthesis equation $M = P^{-1}T$
- the design equation $G = P^{-1}Q$

The idea is, for given plant P, to select proper and stable T so that M is also proper and stable. This insures existence of internally stable controllers. Thus, the synthesis equation displays all possible responses T which have internally stable feedback realizations.

Feedback realizations of M, by controller dynamics G and H, as indicated in Figures 1 and 3, are obtained by applying the controller dynamics design equation $G = P^{-1} Q$. The response matrix T maps to the performance matrix $Q = PG$ in Figure 1 and $Q = PAG$ in Figure 3. The issue of internal stability of closed loop realizations is still under study (4), (5) . However, applications of the synthesis and design equations to numerous examples, including nonminimum phase plants, suggest the conjecture that if M and T are proper and stable, and if no cancellations of right hand plane poles and zeros occur in the open loop matrix products PAGHS (Figure 3), then internal stability of the closed loop is assured. In any event, in the abscence of a complete general theory and proof, doubts on internal stability can be resolved in practise by computer simulations of specific closed loop realizations.

The foregoing ideas and use of the synthesis and design equations are illustrated by examples.

DESIGN EXAMPLES

Two turbine engine examples are given to demonstrate linear multivariable

synthesis with transfer functions. The first design example uses a third order research model of General Electric's J-85 engine with two inputs and two outputs. The second example uses a sixth order model of Pratt & Whitney's F100 engine (11) with four inputs and four outputs. It is a pleasure to acknowledge the computational support of E. J. Olbey, S. A. Stopher and J. W. Wildrick of the Bendix Energy Controls Division.

Example 1

A transfer function matrix of the J-85 engine at sea level, 100% speed condition is given by

$$y = P(s)\, u$$

where y is the output vector and u the input vector. The output vector $y'=(N, T)$ where N is rotor speed, RPM, and T is turbine temperature, °F. The input vector $u' = (W_f, A_j)$ where W_f is fuel flow, pounds per hour, PPH, and A_j is nozzle area, in^2. The plant transfer function is

$$P(s) = \begin{bmatrix} \dfrac{5.6}{(.61s+1)(.016s+1)} & \dfrac{55.7}{(.61s+1)(.06s+1)} \\ \dfrac{.17(1.3s+1)}{(.61s+1)(.23s+1)(.016s+1)} & \dfrac{-1.9}{(.61s+1)(.23s+1)(.06s+1)} \end{bmatrix}$$

Response Specification

A closed loop controller is desired to control the engine so that system response to a step: 1. settles in one second, 2. has no overshoot, 3. obtains zero steady state error. Also, decoupling of the output is desired thus the response matrix T is diagonal. The control problem is pictured by the diagram in Figure 5.

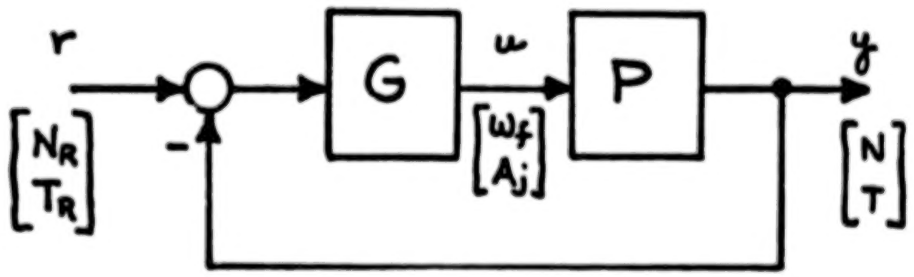


Figure 5 J-85 Engine and Control

Plant Inverse

The plant inverse matrix is calculated first. The plant inverse exists, therefore, a

$$P(s)^{-1} = \begin{bmatrix} .094\,(.016s+1) & 2.8\,(.016s+1)\,(.23s+1) \\ .0084\,(.06s+1)(1.3s+1) & -.28(.06s+1)(.23s+1) \end{bmatrix}$$

meaningful problem is posed; and , it is possible to shape the response of the outputs independently with the available inputs. Decoupled response is possible. The plant has no multivariable zeroes since P^{-1} has no poles. Thus P and P^{-1} indicate that at the given condition, the J-85 engine is a stable plant with no multivariable zeros. No possibility for rhp cancellations from the plant.

Synthesis Equation

The synthesis equation, $M = P^{-1}T$, is applied to determine possible loop responses. Internally stable realizations exist if and only if both M and T are proper and stable. For diagonal T

$$M = \begin{bmatrix} 0.94\,(.016s+1) & t_{11} & 2.8(.016s+1)(.23s+1) & t_{22} \\ .0084(.06s+1)(1.3s+1) & t_{11} & -.28(.06s+1)(.23s+1) & t_{22} \end{bmatrix}$$

M is proper and stable when $t_{11}, t_{22} = \dfrac{K\ (*)}{(T_1 s+1)\,(T_2 s+1)\,(*)}$ form.

Selection of Response Matrix

To meet response specifications, the response matrix T is selected and structured initially as follows:

- diagonal - decoupled response
- predominant time constant = .25 sec - one second settling
- gain = 1 - zero steady state error
- $t_{ii} = 1/(.25\,s \pm 1)\,(*)$ - to satisfy synthesis equation

The above structure of T implies that the performance matrix $Q=T(I-T)^{-1}$ is also diagonal and $q_{ii} = K/s\,(*)$. Of course t_{11} and t_{22} can be chosen differently and independently.

Design Equation

Controller dynamics are computed by the design equation $G = P^{-1}Q$. For diagonal Q

$$G = \begin{bmatrix} .094\,(.016s+1) & q_{11} & 2.8\,(.016s+1)(.23s+1) & q_{22} \\ .0084(.06s+1)(1.3s+1) & q_{11} & -.28(.06s+1)(.23s+1) & q_{22} \end{bmatrix}$$

The above matrix form clearly shows that G is simplified if $q_{11} = q_{22} = K/s(.06s+1)(.016s+1)$. Combining the q_{ii} and t_{ii} requirements gives

$$t_{11} = t_{22} = \frac{1}{(.25s+1)(.08s+1)(.016s+1)}$$

and

$$q_{11} = q_{22} = \frac{2.89}{s\,(.06s+1)\,(.016s+1)}$$

Then controller dynamics are

$$G(s) = \begin{bmatrix} \dfrac{.27}{s\,(.06\,s+1)} & \dfrac{8.1\,(.23\,s+1)}{s\,(.06\,s+1)} \\ \dfrac{.02\,(1.3\,s+1)}{s\,(.016\,s+1)} & \dfrac{-.81\,(.23s+1)}{s\,(.016\,s+1)} \end{bmatrix}$$

Verification

Computer simulation of the J-85 closed loop system (Figure 5) with the above controller dynamics verifies the desired response $T = 1/(.25s+1)(.08s+1)(.016s+1)$. Figure 6 shows the response of the J-85 engine-control system to a 500 RPM step in speed request N_R only. Response specifications and decoupling are achieved. Figure 7 shows system response for 500 RPM step in speed request N_R and -50 degree step in temperature request T_R.

Example 2. F100 Turbofan Engine

An extensive set of linear state descriptions of the F100 turbofan engine were given by Miller and Hackney (11). In this example a reduced model at sea level, 67 degree power lever condition is controlled. This example illustrates a realistic design situation including engine, actuators and sensors. Use of approximate cancellations to simplify the controller is also illustrated.

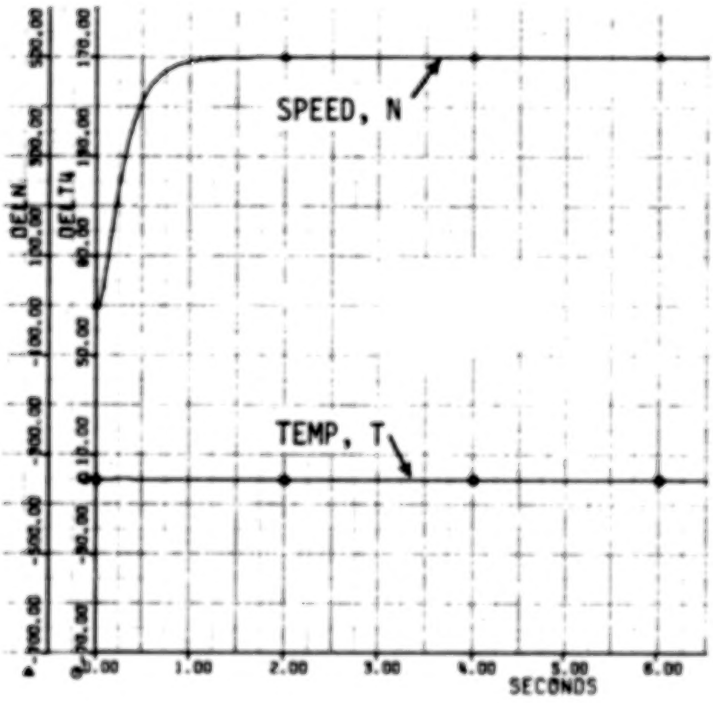


Figure 6. J-85 Response to 500 RPM Step

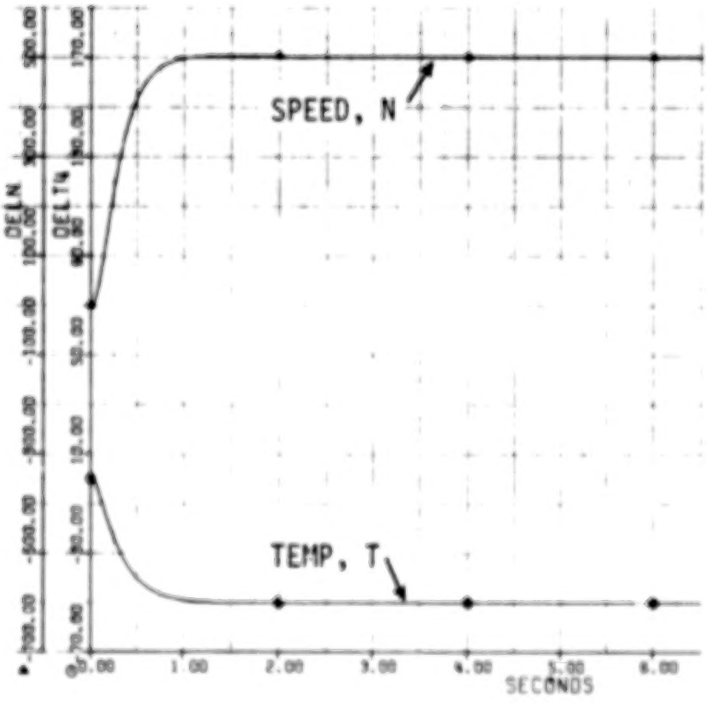


Figure 7. J-85 Response to 500 RPM Step and -50° Temp. Step

Engine Dynamics

A reduced state model of the F100 engine at sea level, 67 degree power lever condition is

$$\dot{x} = A\,x + B\,u$$

$$y = C\,x + D\,u$$

where

$$A = \begin{bmatrix} -4.064 & 3.895 & -470.5 & 7.971 & 5.294 & -3.005 \\ .03718 & -2.958 & -59.13 & .1727 & 2.08 & 12.48 \\ .03389 & .0067 & -4.442 & .0059 & .1474 & .0985 \\ 1.164 & -2.646 & -331.6 & -50.05 & -.473 & -11.36 \\ .05174 & -.1176 & -14.74 & -2.001 & -2.021 & -.505 \\ .00184 & .0036 & -.601 & .00008 & .0009 & -.666 \end{bmatrix}$$

$$B = \begin{bmatrix} .8686 & -14.51 & -96.14 & 9.246 \\ .9096 & -58.46 & -1.053 & -60.15 \\ -.007994 & -79.66 & 1.2 & .3673 \\ 5.643 & -112.2 & -18.23 & 41.53 \\ .2508 & -4.99 & -.8106 & 1.846 \\ .01 & -.3166 & -.02915 & .07426 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \qquad D = \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & & 0 \end{bmatrix}$$

The states, x, inputs, u, and outputs, y, are

x_1 = N_1, fan speed, RPM

x_2 = N_2, compressor speed, RPM

x_3 = P_7, augmentor pressure, PSI

x_4 = T_{hi}, fan turbine temperature (fast), °F

x_5 = T_{lo}, fan turbine temperature (slow), °F

x_6 = T, burner temperature (slow), °F

u_1 = WF, fuel flow, PPH

u_2 = AJ, exhaust nozzle area, FT^2

u_3 = CIVV, inlet vane position, DEG

u_4 = RCVV, compressor vane position, DEG

y_1 = N_1, fan speed, RPM

y_2 = N_2, compressor speed, RPM

y_3 = P_7, augmentor pressure, PSI

y_4 = FTIT, fan turbine inlet temperature, °F

The transfer function matrix of the engine (y = P u) is $P = C (sI-A)^{-1}B + D$ and is shown in Figure 8. In the figure the notation (T s+1) = (T) and (A s^2 + b s +1)=(a,b) is used to save space. A stable, sixth order plant is indicated. The reader will note that the poles corresponding to the time constants (1.43) and (.491) may be eliminated by approximate cancellations; thus, the essential dynamics are fourth order.

$$P = \frac{\begin{bmatrix} .408(1.45)(.501)(.301)(.132)(.009) & 1220(1.43)(.434)(.302)(.0175)(-.0004) & -30.6(1.43)(.493)(.302)(.024)(.018) & -10.6(1.41)(.466)(.309)(-.039)(.014) \\ .326(1.24)(.488)(.03,.308)(.012) & 156(1.18)(.480)(.252)(.013)(-.013) & -1.98(.527)(.290, 1.09)(.021)(.012) & -19.1(1.50)(.483)(.027,.732)(.020) \\ .002(1.32)(.483)(.224)(-.121)(?1) & -7.86(1.47)(.501)(.341)(.256)(.02) & .0248(1.32)(.499)(.475)(.329)(.02) & -.0160(1.43)(-1.44)(.511)(.122)(.02) \\ .695(1.34)(.470)(.377)(.028,.254) & 72.6(1.56)(.470)(.322)(.196)(-.004) & -1.33(1.53)(.470)(.088,.566)(.031) & 1.83(1.54)(.470)(.118)(.035,.144) \end{bmatrix}}{(1.43)(.491)(.302)(.02)(.0297,.236)}$$

Figure 8. F100 Transfer Function Matrix

The plant inverse matrix is shown in Figure 9. The factored form indicates that the inverse has two poles associated with time constants (1.55) and (.470) which are zeros of the plant. Again, these factors approximately cancel from the plant inverse matrix.

$$P^{-1} = \frac{\begin{bmatrix} -.334(1.55)(.470)(.109) & .697(1.55)(.470)(.119) & 42.6(1.55)(.470)(-.007) & 7.75(1.54)(.500)(.013) \\ -.000245(1.54)(.655)(.470) & .000505(1.54)(.470)(-.172) & -.129(*.55)(.470)(.097) & .00270(1.41)(.462)(.008) \\ -.046(1.55)(.470)(.235) & .0450(1.55)(.470)(-.010) & -4.50(1.55)(.470)(.0003) & .160(1.56)(.483)(.002) \\ -.00350(1.50)(.470)(.061) & -.0365(1.57)(.470)(.103) & -.138(1.50)(.470)(-.050) & .144(1.27)(.491)(.015) \end{bmatrix}}{(1.55)\ (.470)}$$

Figure 9. F100 Inverse Matrix

Response Specification

Assume the output response specifications of the F100 engine are 1. decoupled system, 2. step response settles in 1 second, 3. no overshoot, 4. zero steady state error. The desired feedback structure is shown in Figure 10.

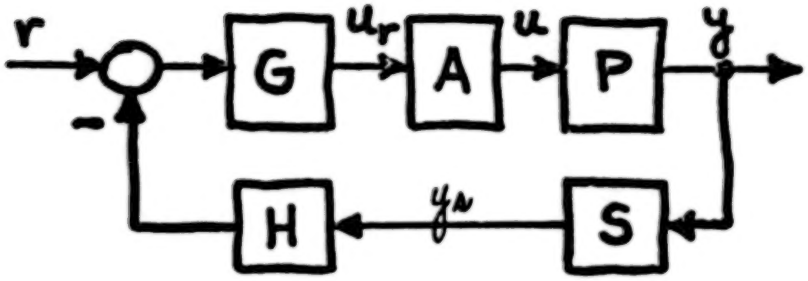


Figure 10. General Feedback Structure

Actuator dynamics are given by $u = A\,u_r$ and sensor dynamics are given by $y_s = Sy$ where

$$A = \begin{bmatrix} \frac{1}{.05s+1} & 0 & 0 & 0 \\ 0 & \frac{1}{.2s+1} & 0 & 0 \\ 0 & 0 & \frac{1}{.1s+1} & 0 \\ 0 & 0 & 0 & \frac{1}{.1s+1} \end{bmatrix}; \quad S = \begin{bmatrix} \frac{1}{.02s+1} & 0 & 0 & 0 \\ 0 & \frac{1}{.02s+1} & 0 & 0 \\ 0 & 0 & \frac{1}{.02s+1} & 0 \\ 0 & 0 & 0 & \frac{1}{.5s+1} \end{bmatrix}$$

Synthesis Equation

The synthesis equation $M = A^{-1}P^{-1}$ becomes

$$M = \begin{bmatrix} -.33(.11)(.05) & t_{11} & .90(.12)(.05) & t_{22} & 42(-.01)(.05) & t_{33} & 7.8(.02)(.05) & t_{44} \\ -.0002(.66)(.2) & t_{11} & .0005(-.17)(.2) & t_{22} & -.13(.1)(.2) & t_{33} & .003(.01)(.2) & t_{44} \\ -.046(.24)(.1) & t_{11} & .045(-.01)(.1) & t_{22} & -4.5(.1) & t_{33} & .16(.01)(.1) & t_{44} \\ -.0035(.061)(.1) & t_{11} & -.037(.40)(.1) & t_{22} & -.14(-.06)(.1) & t_{33} & .14(.02)(.1) & t_{44} \end{bmatrix}$$

M is stable and proper when the t_{ii} form is $K/(Ts+1)(Ts+1)$. Based on the response specifications, $t_{ii} = 1/(.25s+1)(.01s+1)$ is chosen.

Design Equation

The design equation $G = A^{-1}P^{-1}Q$ defines controller dynamics where $Q = T(I - HST)^{-1}$. Using the above T, A, S and P^{-1} matrices and choosing $H = I$, the controller G(s), simplified by cancellations and approximations, turns out to be

$$G \approx \begin{bmatrix} -1.2(.11)(.05) & 3.2(.12)(.05) & 152(.05) & 10(.02)(.05)(.5)/(.16) \\ -.001(.66)(.2) & .002(-.17)(.2) & -.46(.1)(.2) & .004(.01)(.2)\ (.5)/(.16) \\ -.16(.24)(.1) & .16(-.01)(.1) & -16\ (.1) & .21(.01)(.1)(.5)/(.16) \\ -.013(.06)(.1) & -.13(.40)(.1) & -.49(-.06)(.1) & .19(.02)(.1)(.5)/(.16) \end{bmatrix}$$

$$s\ (.01)$$

Verification

System output response of the F100 engine using the above controller was verified by CSMP simulations. Command responses and decoupling for a step request of 4 PSI P_7 augmentor pressure and for a step request of 50 degrees FT1T temperature are shown in Figures 11 and 12 respectively.

SUMMARY REMARKS

Linear multivariable control synthesis with transfer functions appears to be feasible and practical. An output response synthesis method was described using two basic equations both featuring the inverse of the plant transfer function matrix.

The plant inverse matrix is key to multivariable transfer function synthesis. Its existence assures possibilities for plant trackability and decoupling; and, in factored form, it indicates plant zeros, cancellations and potential performance tradeoff to simplify the controller.

Transfer function synthesis builds on classical transfer function concepts, is easy to understand and contacts modern theory. Features include direct design of output response, cancellation and approximation and insight on response adjustments to simplify controller dynamics. The possibility to include both sensitivity specifications and response specifications looks promising and is under study.

Transfer function synthesis is applicable to gas turbine propulsion system design.

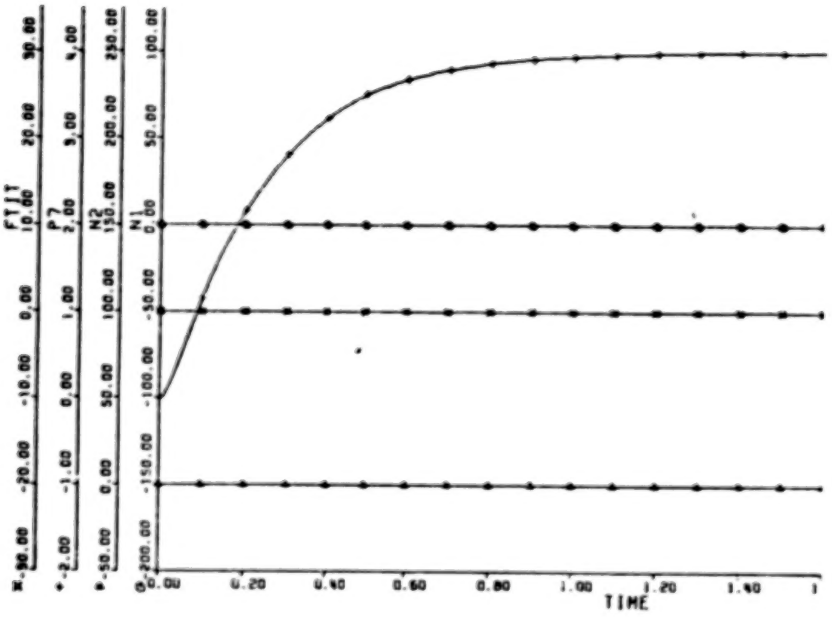


Figure 11. 4 PSI P7 Step

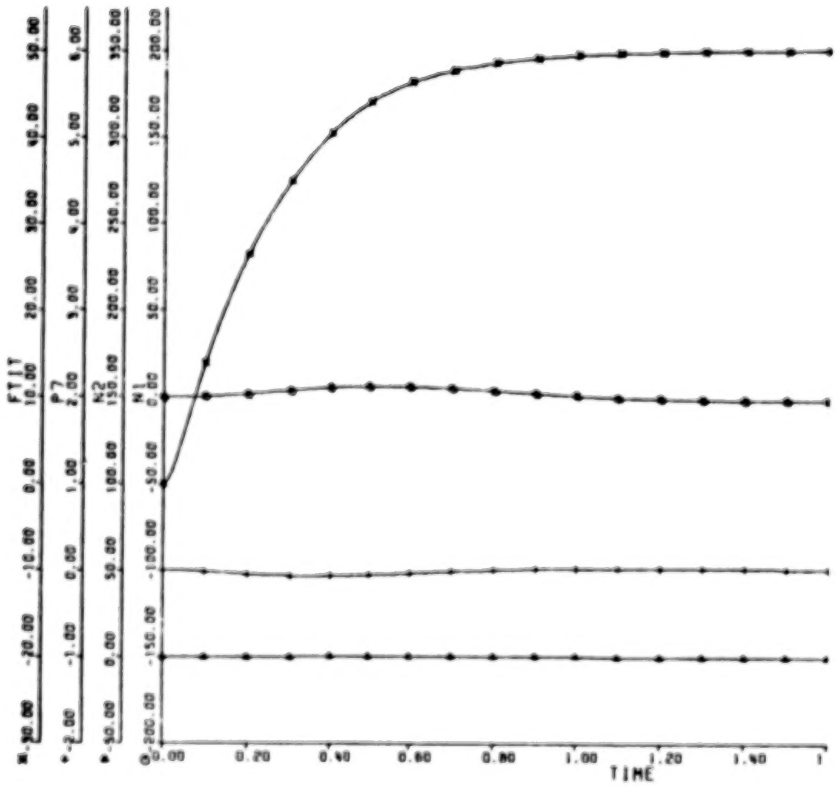


Figure 12. 50 Degree FTIT Step

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ALTERNATIVES FOR JET ENGINE CONTROL*

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SUMMARY

The general purpose of these studies has been to evaluate alternatives to linear quadratic regulator theory in the linear case and to examine nonlinear modelling and optimization approaches for global control. Context for the studies has been set by the DYNGEN digital simulator and by models generated for various phases of the F100 Multivariable Control Synthesis Program. With respect to the linear alternatives, studies have stressed the multivariable frequency domain. Progress has been made in both the direct algebraic approach to exact model matching, by means of stimulating work on the basic computational issues, and in the indirect generalized Nyquist approach, with the development of a new design idea called the CARDIAD method. (The acronym stands for Complex Acceptability Region for DIAgonal Dominance.) With respect to nonlinear modelling and optimization, the emphasis has been twofold: to develop analytical nonlinear models of the jet engine and to use these models in conjunction with techniques of mathematical programming in order to study global control over non-incremental portions of the flight envelope. A hierarchy of models has been developed, with present work focused upon the possibility of using tensor methods. A number of these models have been used in time optimal control studies involving DYNGEN.

INTRODUCTION

The decade of the 1970s has coincided with the beginning of yet another round of substantial development in the jet engine industry. A notable factor involved with this stage of modern engine evolution has been the inevitable growing interest in better and better performance, which in turn placed more and more demands upon the application of classical hydromechanical control technique as the primary base technology for engine design. Fortunately, milestone developments in digital hardware began to offer realistic opportunities for onboard computation in ways not heretofore possible. The combination of these two events pointed the way to a concept of increasing the role of electronics in engine control. In turn, this created a variety of new possibili-

*This work was supported in part by the National Aeronautics and Space Administration under Grant NSG-3048.

**It is a pleasure to acknowledge the many hours contributed by our colleague, Dr. R. Jeffrey Leake, who is no longer associated with this effort.

ties for application of recent theories of control design. The F100 Multivariable Control Synthesis Program (ref. 1) sponsored by the National Aeronautics and Space Administration, Lewis Research Center, and the Air Force Aero-Propulsion Laboratory, Wright-Patterson Air Force Base, is a major example. In the linear case, the primary tool employed was linear quadratic regulator (LQR) theory; in the nonlinear case, optimal control methods were not directly applied.

The purpose of these studies has been to evaluate alternatives to LQR in the linear case and to examine nonlinear modelling and optimization for global control in the nonlinear case.

CONTEXT OF THE STUDIES

Evaluation of various theories for control alternatives has taken place using linearized models related to the F100 Multivariable Control Synthesis Program and using the DYNGEN digital simulator (ref. 2). DYNGEN has the combined capabilities of GENENG (ref. 3) and GENENG II (ref. 4), together with an added capability for calculating transient performance. The DYNGEN digital simulation is particularized to a given situation by a process of loading data for the various maps associated with a given engine. The maps for these studies have been provided by engineering personnel at Lewis Research Center. These maps correspond to a hypothetical engine which is not closely identified with any current engine. But the data do correspond in a broad, general sense to realistic two spool turbofan engines. The simulation provides for two essential controls, main burner fuel flow and jet exhaust area. Portions of the envelope which can be used for linear or nonlinear experimentation are a function of the convergence properties of the DYNGEN algorithm as interfaced with the given engine data load.

MULTIVARIABLE FREQUENCY DOMAIN STUDIES

Modern studies of control in the multivariable frequency domain display various faces in various contexts. Here it is convenient to classify these as "direct" or "indirect".

The direct approach can usually be recognized by its attention to achieving completely specified dynamic performance. The ideas is classical (refs. 5-6). In fact, some of the earliest attempts to expand the direct approach to the multi-input, multi-output case involved work with jet engines (refs. 7-8). As is apparent from reference 7, there is an unfailing tendency to call these methods algebraic in nature. That tendency persists to this day, when direct approaches in multivariable applications typically involve solution for compensations described by matrices of transfer functions, with the solutions often requiring the algebra of modules over rings of polynomials or stable rational functions.

The indirect approaches are usually recognizable by their relation to the classic work of Nyquist. Here the key equation is often written in the manner

$$p_{CL}(s) = |M(s)|\, p_{OL}(s),$$

where $p_{CL}(s)$ is the closed loop characteristic polynomial, $p_{OL}(s)$ is the open loop characteristic polynomial, $M(s)$ is the matrix return difference, and $|\cdot|$ denotes determinant. This very fundamental equation permits an essential generalization of the classical Nyquist idea, for $p_{CL}(s)$ can be used to characterize the exponentials involved in closed loop control. Basically, a Nyquist plot of $|M(s)|$ tends to contain the same type of information which proved so useful in classical design. A great deal of the design effort centers upon the way in which dynamical compensation affects the determinant which acts on $M(s)$. There are three well recognized ways to study this effect. These are (1) direct construction of $|M(s)|$ by any of the known methods for determinant calculation; (2) construction of the eigenvalues of $M(s)$ as a function of s, and use of the idea that the determinant is equal to the product of its eigenvalues (ref. 9); and (3) design of compensation so that $M(s)$ is approximately diagonal, with concomitant development of a relation between the Nyquist plot of $|M(s)|$ and plots of the diagonal elements of $M(s)$, as in reference 10.

THE DIRECT APPROACH

With regard to the direct approach, a substantial case study of exact model mathcing (ref. 11) has been carried out.

The exact model matching problem can be phrased as follows. Let $R(s)$ denote the field of rational functions in s and with coefficients from the real number field R. Further, let V_1, V_2, and V_3 be finite-dimensional vector spaces over the field $R(s)$. Finally, let

$$G_1 : V_2 \to V_3$$

and

$$G_2 : V_1 \to V_3$$

be given linear transformations on one vector space to another. Then the exact model matching problem is to find linear transformations

$$G : V_1 \to V_2$$

of vector spaces, if they exist, such that

$$G_1 G = G_2.$$

In a control problem, G_1 and G_2 are functions of the plant, the complete

closed loop specifications, and the configuration chosen for the controller. The unknown G embodies the dynamics involved in the controller, relative to a fixed configuration of control.

The basic plant was a version of the F100 turbofan engine. Inputs were jet exhaust area and main burner fuel flow; states were fan inlet temperature, main burner pressure, fan speed, high compressor speed, and afterburner pressure; and outputs were thrust and high turbine inlet temperature. The linearized model approximated the small signal behavior of these engine variables in a neighborhood of 47° PLA.

Insofar as the authors are presently aware, this study represents one of the most elaborate exact model matching studies undertaken to date in the literature. Moreover, it is entirely in the spirit of the introductory work in references 7-8.

Technically, the mathematical framework was set up in terms of polynomial modules. The problem formulation itself has been recorded in reference 12, where it can serve as a comparison point for future algorithms. The computer algorithms implemented were those promulgated in the literature at that time (ref. 13).

These studies established several basic conclusions relative to the direct method:

(1) the direct method was of interest in jet engine control (indeed, had been proposed in industrial studies);

(2) the jet engine control problems typical of the 1970s were of sufficient size and complexity to overtax the routine solution procedures being mentioned in the literature at that time; and

(3) a substantial influx of ideas from the literature on numerical methods would be necessary before the direct method could be applied for jet engine control.

It is a pleasure to report that these results did indeed lead to the desired influx, so that computations of sufficient accuracy can now be made in seconds. Efforts involving the direct method are now being directed at the problem of making convenient specifications.

THE INDIRECT APPROACH

Though some efforts (ref. 14) were directed toward the evaluation of the eigenvalue approach (ref. 9) to $|M(s)|$, the major attention under the indirect approach classification in these studies was directed toward the idea of designing dynamical compensation so as to make $M(s)$ approximately diagonal in a way that would be useful in Nyquist studies.

Because of the indirect way in which compensation has an effect on $|M(s)|$, Nyquist analysis of $|M(s)|$ may be of little use to the designer for other than stability determination, for even the simplest systems. In the event that $M(s)$ is diagonal, design and stability considerations are reduced to a set of single input, single output problems, with net angular behavior of $|M(s)|$ being a consequence of summing the individual net behaviors of the diagonal entries.

Rosenbrock (ref. 10) has introduced the idea of diagonal dominance, which can be regarded as an approximate form of diagonality. An mxm matrix $Z(s)$ over $R(s)$ is said to be diagonally column dominant if for all $s \in D$ the Nyquist contour and for $i = 1,2,\ldots,m$

$$|z_{ii}(s)| > \sum_{\substack{j=1 \\ j \neq i}}^{m} |z_{ji}(s)|$$

Rosenbrock shows that, if a matrix $M(s)$ is diagonally column dominant, the net angular behavior of $|M(s)|$ on D can be inferred from that of $\{m_{ii}(s)\}$ on D. Thus the class of matrices for which design and stability analysis may be performed on only the diagonal entries is expanded from diagonal matrices to matrices which are diagonally dominant.

Efforts in these studies have focused upon methods to design compensation in order to achieve diagonal dominance.

The procedure which has been developed is called the CARDIAD method, where the acronym stands for Complex Acceptability Region for DIAgonal Dominance. The CARDIAD idea can be visualized as follows. Consider a unity negative feedback configuration with the mxm plant matrix $G(s)$ preceded by an mxm compensation matrix $K(s)$, both over $R(s)$. Except for renumbering of inputs, the design of $K(s)$ to achieve diagonal dominance may be restricted to $K(s)$ matrices having the unit transfer function 1 in each main diagonal position. This fact is an easy consequence of Rosenbrock's definition. In the CARDIAD approach, a sufficient condition for dominance in the ith column of

$$M(s) = I + G(s)K(s)$$

say, at a particular frequency $s \in D$, is expressed by a quadratic inequality of the type

$$f_i(v) = \langle v, Av \rangle + \langle v, b \rangle + c > 0$$

Here v is a vector in the real space R^{2m-2}, consisting of a list of the real and imaginary parts of the off-diagonal entries in the ith column of $K(s)$ at the particular frequency $s \in D$, $\langle \cdot, \cdot \rangle$ is the usual inner product, A is an Hermitian linear map, $b \in R^{2m-2}$, and $c \in R$. A, b, and c are functions of $G(s)$.

Several different approaches are used to choose v so that $f_i(v)$ is

positive. These are described in detail by references 15-22. References 15-17 deal primarily with engine models having two inputs and two outputs; reference 18 focuses on a three input/output case; and references 6-8 treat four input/output situations.

The basic idea of a CARDIAD plot is easy to understand in the two input/output case. The compensation takes a form

$$\begin{bmatrix} 1 & x_2(s) + jy_2(s) \\ x_1(s) + jy_1(s) & 1 \end{bmatrix}$$

where for $i = 1,2$

$$x_i : D \to R$$

$$y_i : D \to R$$

are the functions defining the real and imaginary parts of the off-diagonal entries in column i. The quadratic inequality can be set equal to its limiting value

$$f_i(x_i(s),y_i(s)) = 0 ,$$

which defines a circle on R^2 with coordinates (x_i,y_i). For a particular $s \in D$, a solid circle is drawn on R^2 if (x_i,y_i) pairs inside the circle satisfy the inequality; and a dashed circle is drawn on R^2 if (x_i,y_i) pairs outside the circle satisfy the inequality. As s traverses D, these circles generate a CARDIAD "plot" on R^2. The plot is essentially a set of requirements, in graphical form, which are necessary and sufficient for compensator design to achieve dominance in the configuration described above.

When $m > 2$, various additional strategies are brought into play. These are described in some detail in the references.

NONLINEAR MODELLING AND OPTIMIZATION

With respect to nonlinear modelling and optimization, the emphasis has been twofold; to develop analytical nonlinear models of the jet engine deck and to use these models in conjunction with techniques of mathematical programming in order to study global control over non-incremental reaches of the flight envelope. The context for such studies has been established by DYNGEN, as described above.

The first method of modelling which was considered was that of analytical construction of the equations from the basic physical principles. In this case, there were sixteen nonlinear differential equations, as well as a large number of nonlinear static functions which provided additional coupling among the

equations. Such a procedure then requires determination of parameters in the equations. A number of these parameters have very definite physical meanings, and these meanings were supplemented by simulation data when appropriate. Obtaining tractable models for the engine in this way, though promising from the point of view of physical insight, did not lead to very much mathematical insight. Subsequently, therefore, this method gave way to the following.

The second method of modelling placed increased emphasis upon the mathematical structure of the equations, with determination of parameters being done automatically from simulator data. A highlight of this part of the study was the development of the model class

$$\dot{x} = A(x)\ (x-g(u))$$

where $x \in R^n$, $u \in R^p$. The function g is arranged so as to satisfy the set-point or steady-state features of the engine deck, while the operator

$$A : R^n \to R^n$$

is useful to adjust the transient behavior of the model. The particulars of this idea were described in reference 23.

A number of possibilities exist for approaching the approximation of $A(x)$ and $g(u)$. One additional method and application has been presented in reference 24.

At this point in time, a new stage in the nonlinear modelling studies is being initiated. In this phase, extensive use will be made of the methods of multilinear algebra, specifically the theory of algebraic tensors.

Models of the types evolved in phases one and two have been used in time-optimal control studies. Results of these efforts have been written down in references 25-27.

CONCLUDING REMARKS

This brief paper has sketched a number of control alternatives which have been studied recently in the context of the DYNGEN digital engine simulator and of linear models deriving from the F100 Multivariable Control Synthesis Program. In the linear case, these studies have focused on alternatives to the linear quadratic regulator theory employed in that Program. In the nonlinear case, emphasis has been placed on nonlinear modelling and time-optimal control.

Principal results reported have been the case study on exact model matching, which has stimulated considerable new work in that problem area, the development of the CARDIAD plot as a design tool for generalized Nyquist work, and the introduction of a nonlinear model class which is proving to be helpful in recent engine design studies.

Present thrust in this work is toward the use of multilinear algebra for generalized nonlinear modelling.

Finally, the reader may be interested in the fact that the National Engineering Consortium sponsored an International Forum on Alternatives for Linear Multivariable Control in Chicago during October 1977. Authors in that meeting were asked to address a Theme Problem based upon F100 data. Two publications resulted, one a proceedings and one a hardbound book. Reference 23 is to the proceedings, while reference 18 is to the book. Much additional information may be found in those volumes.

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SENSOR/ACTUATOR FAILURE DETECTION FOR TURBOFAN ENGINES

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SUMMARY

The demand for higher performance levels of turbofan engines has resulted in the development of increasingly more sophisticated air breathing engine design configurations. As the performance demands become more restrictive, the number of manipulated inputs increase in correspondence with the increase in the number of controlled outputs. Thus, from a control system design viewpoint, the engine must be treated as a multi-input-multi-output system. The control design may then proceed using modern design methodologies in either the time domain or in the frequency domain.

Inherent to any successful control system design is the requirement to accurately record on-line engine performance and to reliably actuate the control input signals. A failure of any sensor or actuator used by the controller can lead to significantly reduced performance levels. The extent of the performance reduction is determined by the source and type of failure and the dependency of the design methodology on that information.

Traditionally, the problem of sensor/actuator failure has been resolved through the utilization of redundant components. The failed component was then easily detected using standard voting procedures. As turbofan engine designs become more complex, hardware redundancy becomes more impractical. With the introduction of on-board digital computers for flight control (F100 and QCSEE) hardware redundancy may be replaced with analytical redundancy.

For time domain control procedures requiring the full state vector for control actuation the residuals of the Kalman-Bucy filter may be examined for "whiteness." If the statistics associated with the residuals depart from the white noise condition, then a failure is declared. Willsky and Jones [1] use this concept to develop a procedure for sensor/actuator failure detection using a Generalized Liklihood Ratio (GLR) hypothesis test. Since the sensor data is used to generate state estimates which are then used to reconstruct output estimates for detector evaluation, the number of failure modes considered by the detector is large. Thus, detection time increases in direct proportion to the number of failure modes considered.

If the feedback control design does not require an estimate of the state vector, as in the case of the Multivariable Nyquist Array Method (MNA) [2,3], the Kalman filter "model" of the system is no longer required. Thus, the "residuals" can be generated by comparing the sensor outputs with a similar set of outputs generated by an accurate non-linear simulation model. The concept of the GLR can then be retained to provide a reliable evaluation of sensor or actuator operation since sensor outputs are no longer needed to provide data estimates. Figure 1 diagrams the proposed failure detection procedure using a simulation model.

The development of the proposed GLR detector using model residuals utilizes the following assumptions:

A. The physical system may be non-linear with outputs contaminated by zero-mean additive white noise of known intensity.

B. The on-board digital computer is of sufficient size for storage of the noise-free nonlinear simulation of the plant, the detection software and the feedback controller.

C. The residuals are zero mean when no failure exists.

D. Under a failed sensor or actuator the residuals have non-zero mean.

E. It is desirable to estimate which sensors or actuators failed, the form of failure occurring and the time the failure occurred.

F. An observation "window" of finite dimension is to be used for failure detection to reduce storage and computational requirements.

G. The set of failure modes is finite and is known a priori.

Utilizing these requirements a GLR detector was developed for hard-over failure conditions of the following type:

1. Actuator step failures

2. Brief disturbances in actuator output

3. Sensor step failures

For each case a hypothesis test was established for comparison with the null hypothesis (i.e., no failure condition). The GLR was formed, data window widths selected for low probability of false alarms and cross detection. Threshold levels are then established from these requirements.

The performance of the proposed GLR method was evaluated by application to the General Electric QCSEE turbofan engine [4]. Using the non-linear simulation for the under-the-wing model of QCSEE developed by Mihaloew [5] the output sensor measurements PS11, NL, NH, P12, P4, and T3 were corrupted by white noise to represent the physical engine. The actuators considered were those associated with the fuel metering valve position, fan nozzle area position, and the fan pitch mechanism drive motor position. A duplicate software program was used to represent the plant model as indicated in Figure 1.

For the application considered here, the 62.5% of full power condition was used. For the actuator and sensor failure conditions cited above, the GLR detector accurately diagnosed the failure type and identified the failed component correctly in every case. In addition, the GLR detector correctly identified the time at which the failure occurred. A representative plot of the GLR index is presented in Figure 2.

To obtain the data of Figure 2, the GLR index for each actuator and sensor is computed for all assumed failure modes. A comparison of all indices is made and the largest index is selected at each time step and plotted. Prior to the actual induced failure ($K = 10$) the maximum GLR index is non-definitive since no failure has occurred and the index remains below the established threshold ($\varepsilon = 34$). With an induced failure in PS11 (at $K = 10$) the detector correctly identifies the sensor and the failure time. The threshold of $\varepsilon = 34$ is established prior to any test runs and is strictly a function of the data window length, the pre-established probability of a false alarm, and the covariance of the sensor noise.

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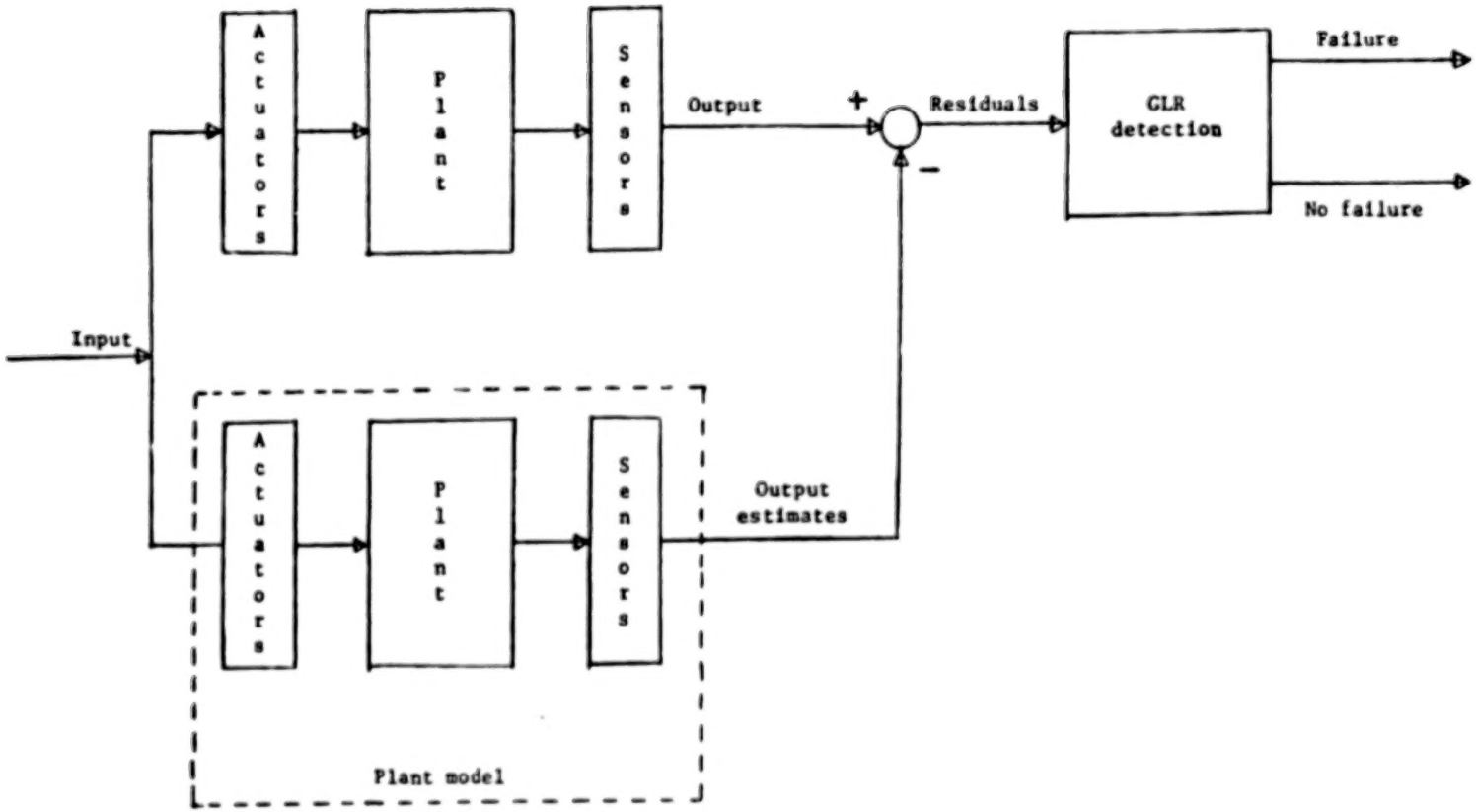


Figure 1. - Failure detection with plant model.

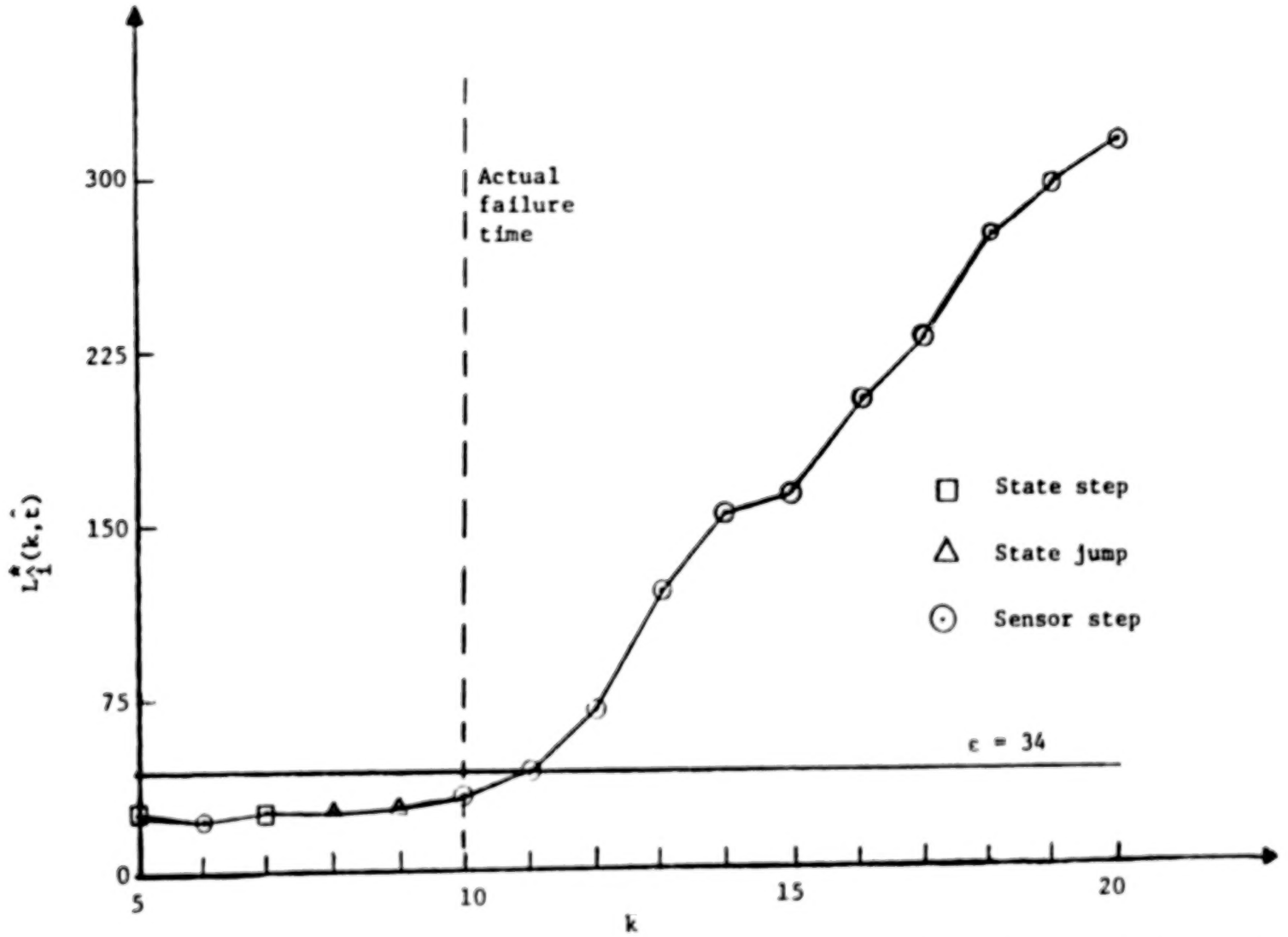


Figure 2. - Maximum GLR index for sensor-step failure in PS11 as function of observation number.

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WORKSHOP AND OPEN DISCUSSION

A workshop and an open discussion were included in the symposium. These sessions gave each attendee the opportunity to present his own views on pertinent research topics and to help direct future research in multivariable engine control. Each session is described here, and a summary of the results is presented.

Workshop

The workshop consisted of groups of 8 to 10 people seated at separate tables. A chairman was assigned to each group to lead the discussion. Group chairmen included Daniel Drain, John Zeller, John Szuch, James Sellers, Peter Batterton, and Bruce Lehtinen from the Lewis Research Center; Les Small and Charles Skira from the Air Force Aero Propulsion Laboratory; and F. W. Burcham from the Hugh L. Dryden Flight Research Center.

As a guide for discussion several topics were devised for the workshop. However, discussion was not necessarily to be constrained by these topics, which were

(1) Rank the following theory areas in order of decreasing importance to propulsion control: nonlinear optimal control techniques; sensor-actuator failure accommodation logic; system identification; multivariable frequency domain control methods; adaptive control; multivariable control theory (LQR, OFR, etc.); estimator design; and nonlinear engine modeling. Include other areas if appropriate.

(2) Do you feel that the F100 MVCS control methodology has been sufficiently demonstrated, is mature enough, and presents adequate payoffs of justify incorporating this control structure into the next generation of production engines? What is the most significant technical or political problem to be overcome in the successful incorporation of this technology in a production system?

(3) Does a totally integrated propulsion control system (engine-airframe-inlet) generate enough payoff in military and commercial aircraft to justify the cost of the more sophisticated control? What is the most significant technical or political problem to be overcome in the successful incorporation of total integration into a production system?

(4) What single theoretical advance or application of new theory can most significantly advance the state of the art in propulsion system control?

(5) NASA will develop a research aircraft over the next 3 years as part of the IPAC program. One of the two engines in this converted F-15 aircraft is to be controlled by a programmable on-board digital computer. What is the most significant research application relating to propulsion control for which this aircraft can be used?

(6) Can state-of-the-art adaptive control techniques be successfully applied to engine control systems to minimize loss of performance in the face of component degradation and engine-to-engine variation?

(7) Given the distributed nature of future engine control systems and the trend toward engine-airframe integration, how many of the engine control system functions can be moved off the engine?

Comments of the participants in the workshop were summarized and recorded by each chairman. The following is a compilation of these recorded comments.

Group one dispensed with the questions and discussed (1) the maturity of multivariable techniques for the design of engine controls, (2) the adequacy of presently available models for propulsion systems, and (3) the problem of airframe - propulsion system integration.

A mature control design technique was defined to be a technique well enough understood in terms of its usefulness and limitations that a potential user would not be deterred from its use. A university representative stated that both the time- and frequency-domain multivariable techniques are by this definition "mature." However, there is much still to be done in frequency-domain techniques although they are usable today. An industry representative from a "control house" did not agree and said that they are not now using frequency-domain methods and will probably not be in the near future.

There was almost unanimous agreement on the modeling problem. Adequate methods of describing the engine process, especially for controls analysis and design, are lacking. This area needs work.

It was agreed that a major management (political) problem exists in the integration of aircraft propulsion controls for manned aircraft. A representative from the drone and remotely piloted vehicle area said such integration is common practice with these types of vehicles. However, in terms of manned aircraft someone must look at the total problem and set performance specifications for the propulsion system and airframe. This is not now being done rigorously to obtain the best system performance.

Group two followed the session topics, with the following results:

Topic 1 - Nonlinear engine modeling is the most important theory area because of its importance to all aspects of control. Emphasis should be placed on simplifying complex, nonlinear thermodynamic decks. Related to nonlinear modeling, the whole problem of nonlinear optimal control needs to be addressed. Also, good models are needed in any application of sensor detection-accommodation methods. The general feeling exists that adequate attention is being paid to multivariable control methodology such as LQR (linear quadratic regulator) and frequency-domain methods. However, estimators are needed to increase mission reliability and to lower costs by reducing the numbers of sensors and sensor redundancy. Adaptive control payoffs do not warrant the increased control complexity, the difficulty in certifying the control, etc. Also, it was felt that current approaches to actuation and servofeedback are adequate in terms of tolerance to failure. Areas of importance are fuel flow and compressor geometry.

Topic 2 - The feeling is that LQR is a small part of the total MVCS (multivariable control system). In spite of MVCS modularity and systematic regulator design, problems of schedule development and transition control need to be addressed. The technique could be applied as a tool in future engine control development, even for an F100 type of engine and especially for a more complex VCE (variable-cycle engine). Problems are foreseen in demonstrating its suitability in terms of debugging, understandability, and maintenance when compared with current systems. Industry needs to know more about the program and associated problems, etc.

Topic 3 - Payoffs are expected in supersonic and VTOL (vertical takeoff and landing) applications but not in commmercial subsonic transports. Integration of control functions is needed, but there are practical problems associated with integrating the hardware. Reliability, flight safety, and the need for close-coupled sensors, actuators, etc., will influence the use of distributed computers, etc. Development of standard interfaces and data buses (like the MIL 1553) will aid in the integration of control systems. Although there is a real political problem in sharing responsibility for system integrity, examples were given where total integration has been attempted, such as in weapon systems (unmanned). In this case the cost factor was very important. Dispatch reliability requirements will outweight cost benefits and performance benefits in commercial applications, and this suggests distributed-architecture implementations.

Topic 4 - Nonlinear modeling theory will most significantly advance the state of the art in propulsion systems control. The emphasis should be on model simplicity and accuracy.

Topic 5 - Data communication and control integration are the most significant research applications for which an INTERACT (IPAC) program aircraft could be used.

Topic 7 - It was the opinion of the group that very few of the engine control system functions could be moved off the engine.

Group three did not follow the discussion topics but discussed electronic control mounting locations for improved reliability and F100 MVCS followon work. One question raised was the reliability of off-engine-mounted electronics as compared with on-engine-mounted electronics. The consensus of opinion was that most problems were with quality control. Extensive burn-in tests at the manufacturer's plant were a must. A typical rejection rate was 70 percent on the first pass. The consensus also was that the F100 control logic should be expanded to include afterburning, mode selection, expanded performance considerations, etc., rather than flight testing the same logic already evaluated in NASA's altitude test facility.

Group four followed the discussion topics:

Topic 1 - Priorities were assigned as most important, less important, and least important to the different theory areas for both near-term and long-term

applications. For the near term, modeling and system identification were given highest priority. Multivariable control design, both in the frequency and time domains, was given lesser priority; estimation and fault accommodation were designated as least important. Most important long-term applications were selected as adaptive and nonlinear control.

Topic 2 - Work in the F100 MVCS established a valuable benchmark, although more work is definitely required. Two approaches to extending multivariable control work were considered, given a fixed level of resources. A narrow approach would be to pursue one approach (the F100 MVCS, e.g.) as far as possible with the available resources. Probably its logical conclusion would be a flight test. A broad approach would look at a wide variety of techniques, pick the best, and then proceed. In this case resources probably would not be allocated to a flight. There is a general need for an engine testbed (similar to the F100 MVCS simulation) that is accessible to many for evaluation of control techniques. Finally, it was stated that there is a need for a flight test of new control techniques in order for these new techniques to <u>begin</u> to be accepted politically.

Topic 3 - It was felt that the answer was application dependent. For commercial airline applications controls integration is not necessary but provides some payoff. However, in a VSTOL application airframe - propulsion system controls integration is an absolute necessity. A number of small applications-and-benefits studies have been done, but most are proprietary. There is a need for a broad look at this topic and for the results to be made available to all interested parties. A political problem would arise when deciding who is responsible for what control action. This becomes a management problem. Also, it must be decided what the interface mechanism is for the airframe manufacturer, the engine company, and the flight control company. The consensus of opinion of this group was that the airframe manufacturer must take overall charge (and therefore overall responsibility).

Topic 4 - The most important research application of an INTERACT (IPAC) aircraft would be an integrated MVCS control carefully developed in a sequence of logical technical steps.

Topic 5 - State-of-the-art adaptive control techniques cannot yet be applied to engine control systems.

<u>Group five</u> also followed the discussion format:

Topic 2 - With respect to the demonstrated maturity of the F100 MVCS methodology, it was felt that a flight test of this type of logic would be very effective in getting management acceptance and also in getting new users in the engine community to use multivariable design methods. The high cost of a dedicated flight test for only MVC makes it necessary that testing be done as part of a program such as INTERACT. There is a problem with the proper dissemination of results of demonstration tests to potential users. System studies and simulation work will not assure the transfer of new technology. Flight tests have much more influence in demonstrating hardware.

Topics 3 and 4 - There is a need for integrated control for systems using mixed-compression inlets. Severe interactions can exist between the inlet, the aircraft, and the engine. The application of MVC logic to the problem was discussed. It was not clear that LQR would be designed for complete systems. Multivariable control is not necessarily the most significant problem but the one discussed with respect to the INTERACT application program.

Open Discussion

The open discussion immediately followed the workshop and served as a forum for each attendee to discuss the results of the workshop with the entire group. It was felt that this format would facilitate the airing of minority opinions on any given topic. This section summarizes the transcript of this session. The summary does not stress completeness nor the rigorous word-for-word reproduction of individual statements. It does, however, attempt to provide the flavor of the discussion and to document the interesting or significant comments. The discussion was structured to address four general topics (1) engine models, (2) control design, (3) integrated control, and (4) expectations.

Engine models. - The emphasis was on the sophistication and accuracy required of an engine model and the uses to which that model would be put. What level of modeling accuracy is required for control design? Also, how should these models be determined? Particular importance was attached to simplified, nonlinear simulations and the techniques or theory required to generate these accurate yet simple models. It was felt that this was an important step for future failure accommodation work. The question also arose as to how a researcher who is not directly connected to an engine manufacturer can get access to a real, or at least plausible, engine digital simulation. Such a simulation would incorporate detailed steady-state and transient characteristics and should include sensor and actuator models as well. It was pointed out that a common simulation, available to all, would be a good basis for a round-robin competition to evaluate various techniques in engine model identification or control design. It would be a good vehicle to demonstrate potential benefits from more sophisticated control strategies.

With respect to engine model identification, several interesting ideas were discussed. Given the nature of complete demonstrator engines like QCSEE or a VCE or even the F100 engine during the engine development process, good engine models are not available at the time the engine is first put on a testbed. Also, most of the data taken during these initial engine tests are not compatible with improving or modifying the engine model for the next engine test. As a result controls engineers are typically one or two engine builds behind because they do not have a simulation that matches the current engine build. Identification techniques, however, could be used to develop an automated procedure to generate improved, updated models from test data. Such an automated procedure would require a minimum of additional dedicated test time. The identified model could then be used in place of a detailed, nonlinear simulation for control design.

It was mentioned that controls work typically receives a low priority during initial engine tests. Generally, because of the high cost of engine tests,

engineers try to "get off" the engine and go to a closed-loop bench test as soon as possible. It is very difficult to justify dynamic testing versus steady-state performance testing because of engine test costs. Additionally, experimental engines are treated very carefully, and engine inputs would be severely constrained in any identification test. There is a continuing need on the part of the controls community to fight the battle with management for higher priority test time during engine testing.

An alternative point of view was expressed about engine modeling. Controls development is not constrained. That is, one can adjust control gains as the engine evolves. This approach is inconvenient, but it does not result in poor control systems. Therefore it may not be necessary to have 100-percent-accurate models since control gain accuracy compromises are always made during this evolutionary process. A model with, for example, 90 percent accurate prediction of trends would be adequate because, regardless of the sophistication of the control computer schedule and bias, compromises are made when implementing a control. Thus analytically derived models are adequate for control work. This point was questioned as not universally true or at least not universally agreed upon. It was felt, however, that identification techniques would be useful or even required for integrated control systems to develop total system trends. Also, identification work for failure accommodation or engine condition monitoring requires a good reference (detail and accurate simulation) upon which to base simplifications.

Control design. - Generally there was lengthy discussion on the relative maturity of the F100 MVCS control (LQR) methodology as applied to engines. The discussion first addressed a definition of maturity. One definition describes a mature design technique as one that a controls designer could use with confidence to develop a practical control. That is, a designer could be confident that he could arrive at an acceptable control design with this technique. Another commented that the Government (Air Force and Navy) places emphasis on the flight demonstration of engines to demonstrate maturity before a commitment to a major development program. From this point of view a design technique is not mature until a flight demonstration of the hardware implementing such a control design. It was pointed out, however, that demonstration of the MVCS approach was basically a demonstration of software. Also, there is great difficulty in justifying a flight test to demonstrate software alone.

Another viewpoint was that regardless of the definition of maturity the real issue was the practical use of the technology in a production engine. The question now becomes one of technology transfer and how the transfer is best accomplished. Meetings and symposia are important in this regard, but a clear-cut demonstration of design or performance benefits was said to be decisive in the acceptance of the technique. Possible benefits of the MVCS approach include flexible control modes and a high degree of confidence that a suitable design can be obtained in a reasonable time.

Concerning multivariable control system design in its broadest sense, there are two alternative research approches. First, there could be a number of small university grants in a limited area with long-term payoff (10 to 20 yr). Second, there could be a large-scale effort to develop a practical multivariable

control design for a specific engine, with a short-term (5 to 10 yr) payoff. Payoff implies that the approaches become understood and accepted practice by the engine and controls manufacturers and eventually result in a production application. The transition of this technology will be accelerated by the competitive nature of the engine development and acquisition process if, and only if, an approach demonstrates an advantage over existing techniques. This advantage could be a more orderly, step-by-step design procedure that always yields an acceptable control or the ability to improve overall system performance.

Although most attendees agreed that the F100 MVCS design procedure was mature enough to use in a practical sense, there was less agreement as to the relative maturity of multivariable frequency response techniques. In this regard a complete comparison of frequency-domain techniques to the F100 MVCS control was suggested. Since the F100 MVCS control has been thoroughly evaluated on a real-time, hybrid simulation, and since this control subsequently was tested in an altitude test facility and gave good agreement with simulated results, the F100 hybrid simulation was considered an ideal testbed for the comparison. It was pointed out, however, that such a test would require personnel already committed to other projects. Alternatives were explored, including the use of the QCSEE simulation as an equivalent testbed. A final comment made in this area related the difficulty of convincing management to allow designers to apply advanced multivariable techniques to control problems. It was pointed out, however, that management generally would not specify the design technique to be used. Rather a designer would be free to choose his own technique. Management would simply require justification in this selection.

Integrated control. - This topic concerns the integration of propulsion-airframe-inlet control systems into a single system. One opinion was that multivariable control is suitable to the entire integration problem but that a total multivariable, integrated control is unlikely. Inevitably the integrated control would be segmented to some extent at the expense of total system integration. A question was raised as to the necessity of integrated systems. Examples of aircraft that require integration are VTOL and high-performance supersonic aircraft that can demonstrate severe interactions between individual systems.

The next issue discussed was the allocation of control tasks to various pieces of hardware in an integrated system. One possibility is an airframe-mounted central computer handling all control functions including propulsion control. Another possibility is an hierarchical system, where individual control tasks are performed "at the site" and communications are established from these on-site controllers to a master computer. The importance of removing the control electronics from the harsh engine environment was mentioned. Various legal and political difficulties in removing the control electronics from the engine environment were also discussed. These included establishing liability in the event of an engine failure and overall responsibility for control design and operation. It was pointed out by an engine manufacturer's representative that, in the field of business jets, economic factors have already led to some degree of integration. Four particular areas were mentioned (1) off-engine mounting of controls into an environment more suitable for computers, (2) aircraft interconnecting cabling, (3) sensors that are furnished by the aircraft manufacturer, and (4) input devices that are console mounted.

Other examples of successful integration followed, particulary in unmanned vehicles like the Cruise missile. In this case an on-board, sophisticated computer provides navigational and guidance control as well as weapons arming control. This computer does not control the fuel metering valve, however. The Cruise missile would be an ideal candidate for studies in total interactive control (including the fuel valve) because of the demands of terrain following and the resultant airflow variations.

A general request was made for more interaction between flight control designers, airframe manufacturers, and engine control designers to hasten work in system integration. It was announced that NASA is planning a major effort in avionics and controls. Some of the goals will be the evaluation of propulsion controls, the use of digital electronics, and the study of interaction in VTOL aircraft.

Expectations. - Participants in the discussion session were asked to comment from their particular perspective on their expectations of the roles of universities, industry, and Government. An industry representative encouraged university researchers to channel their research to directly applicable work. Such work should make fewer assumptions and be directly applicable to real-world problems. Another industry representative wanted responsible reporting of research. This would mean reporting results that are both good and bad when they exist and presenting desirable results along with the costs required to obtain those desirable results. His expectations of the Government included a runoff competition between the F100 MVCS (LQR) design methodology and the multivariable frequency-domain techniques on an engine testbed (F100 simulation).

A university representative agreed that university researchers do not have a good appreciation of industry problems and that as a result their research is not applicable in the near term. The responsibility or role of industry should be to communicate to university researchers a knowledge of which projects are important and what problems they would like to see solved. In this regard a testbed simulation or other engine modeling information should be made available to university people.

A second university researcher saw his own role as a broker of ideas. His job is to interpret the wealth of theory that now exists to help industry use or reject those theories, which may apply to any given problem. Industry has the obligation to "weed out" the good and the bad theories that do apply. Industry seminars are one method to improve university-industry interactions. Also, the Government should recognize that it requires an investment of time to evaluate new ideas.

A Government representative saw Government's role with universities as twofold. First, the Government should establish a base of university expertise by funding propulsion-related research. Second, NASA wants to develop and interest graduate students in propulsion control. Industry's responsibility is to get the propulsion control problem higher on the list of management priorities. Also, industry should jointly work on an engine testbed.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CP-2137		

4. Title and Subtitle	5. Report Date
PROPULSION CONTROLS, 1979	October 1980
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No. E-477
	10. Work Unit No.
9. Performing Organization Name and Address NASA Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Conference Publication
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

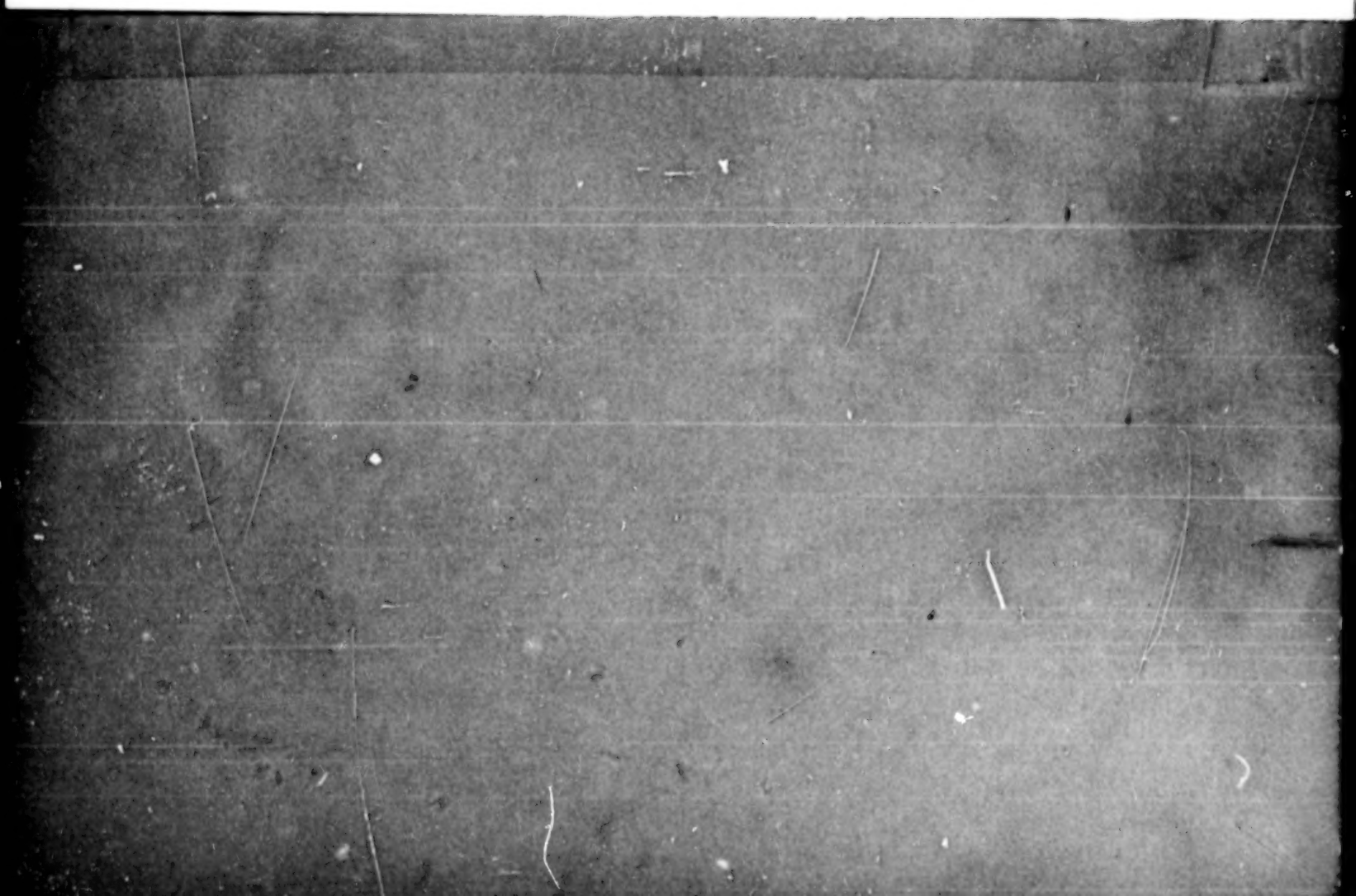
This publication records the proceedings of the 1979 Propulsion Controls Symposium held May 17-19, 1979 at the NASA Lewis Research Center in Cleveland. The symposium brought together industry, Government, and university researchers interested in air-breathing engine control to review the present state of multivariable engine control, to determine future needs and problem areas in engine control design, and to determine the appropriate roles of Government, industry, and universities in addressing these problems. Papers presented at the symposium and included herein deal with engine model identification, performance-seeking logic, multivariable control theory and applications, and sensor failure detection. Other papers by the Air Force, NASA, engine manufacturers, and airframe manufacturers assess these problems and the future needs of propulsion systems. Results from the workshop and open discussion are also summarized herein. The topics discussed included the relative maturity of multivariable engine control, the relative importance of various competing multivariable design techniques, interactive airframe and engine control, and the roles of Government, industry, and universities in engine control research.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Linear quadratic controls; Identification; Sensor failure detection; Turbine engines; Multivariable Nyquist: Digital control; Integrated control	Unclassified - Unlimited Subject Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	152	A08

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1980



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March 6, 1981